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# Measurements of prompt charm production cross-sections in $pp$ collisions at $\sqrt{s} = 5$ TeV



## The LHCb collaboration

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**ABSTRACT:** Production cross-sections of prompt charm mesons are measured using data from  $pp$  collisions at the LHC at a centre-of-mass energy of 5 TeV. The data sample corresponds to an integrated luminosity of  $8.60 \pm 0.33 \text{ pb}^{-1}$  collected by the LHCb experiment. The production cross-sections of  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^{*+}$  mesons are measured in bins of charm meson transverse momentum,  $p_T$ , and rapidity,  $y$ . They cover the rapidity range  $2.0 < y < 4.5$  and transverse momentum ranges  $0 < p_T < 10 \text{ GeV}/c$  for  $D^0$  and  $D^+$  and  $1 < p_T < 10 \text{ GeV}/c$  for  $D_s^+$  and  $D^{*+}$  mesons. The inclusive cross-sections for the four mesons, including charge-conjugate states, within the range of  $1 < p_T < 8 \text{ GeV}/c$  are determined to be

$$\begin{aligned}\sigma(pp \rightarrow D^0 X) &= 1004 \pm 3 \pm 54 \mu\text{b}, \\ \sigma(pp \rightarrow D^+ X) &= 402 \pm 2 \pm 30 \mu\text{b}, \\ \sigma(pp \rightarrow D_s^+ X) &= 170 \pm 4 \pm 16 \mu\text{b}, \\ \sigma(pp \rightarrow D^{*+} X) &= 421 \pm 5 \pm 36 \mu\text{b},\end{aligned}$$

where the uncertainties are statistical and systematic, respectively.

**KEYWORDS:** Charm physics, Forward physics, Hadron-Hadron scattering (experiments), Heavy quark production, QCD

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**1 Introduction**

Measurements of charm production cross-sections in proton-proton collisions are important tests of perturbative quantum chromodynamics [1–4]. Predictions of charm meson cross-sections have been made at next-to-leading order using the generalised mass variable flavour number scheme (GMVFNS) [3, 5–9] and at fixed order with next-to-leading-log resummation (FONLL) [1, 2, 10–13]. These are based on a factorisation approach, where the cross-sections are calculated as a convolution of three terms: the parton distribution functions of the incoming protons; the partonic hard scattering rate, estimated as a perturbative series in the coupling constant of the strong interaction; and a fragmentation function that parametrises the hadronisation of the charm quark into a given type of charm hadron. Predictions are also obtained from Monte Carlo programs implementing NLO perturbative QCD, where the partonic final state is matched to parton shower simulations [1]. The range

of rapidity,  $y$ , and of the momentum component transverse to the beam axis,  $p_T$ , accessible to the LHCb experiment enables quantum chromodynamics calculations to be tested in a region where the momentum fraction,  $x$ , of the initial state partons can reach values below  $10^{-4}$ . In this region the uncertainties on the gluon density function are large, exceeding 30% [1, 14], and LHCb measurements can be used to constrain it. This paper presents measurements of charm hadron production cross-sections at a proton-proton centre-of-mass energy of  $\sqrt{s} = 5$  TeV. Ratios of cross-sections at different  $\sqrt{s}$  benefit from cancellations in experimental uncertainties on the measured cross-sections as well as theoretical uncertainties on the predictions [2], allowing for precise comparisons. Measurements of charm production cross-sections in  $pp$  collisions at  $\sqrt{s} = 5$  TeV also define the reference for the determination of nuclear modification factors in heavy ion collisions at that nucleon-nucleon centre-of-mass energy, recorded in 2015 at the Large Hadron Collider (LHC).

Measurements of charm production cross-sections in hadronic collisions have been performed in different kinematic regions and for various centre-of-mass energies in the TeV range. Measurements by the CDF experiment cover the central rapidity region  $|y| < 1$  and transverse momenta,  $p_T$ , between 5.5 GeV/ $c$  and 20 GeV/ $c$  at  $\sqrt{s} = 1.96$  TeV in  $p\bar{p}$  collisions [15]. At the LHC, charm cross-sections in  $pp$  collisions have been measured in the  $|y| < 0.5$  region for  $p_T > 1$  GeV/ $c$  at  $\sqrt{s} = 2.76$  TeV and for  $p_T > 0$  GeV/ $c$  at  $\sqrt{s} = 7$  TeV by the ALICE experiment [16–19], and for pseudorapidity  $|\eta| < 2.1$  in the  $p_T$  region  $3.5 < p_T < 100$  GeV/ $c$  at  $\sqrt{s} = 7$  TeV by the ATLAS experiment [20]. The LHCb experiment has recorded the world’s largest dataset of charm hadrons to date and this has led to numerous high-precision measurements of their production and decay properties. LHCb measured the cross-sections in the forward region  $2.0 < y < 4.5$  for  $0 < p_T < 8$  GeV/ $c$  at  $\sqrt{s} = 7$  TeV [21] and for  $0 < p_T < 15$  GeV/ $c$  at  $\sqrt{s} = 13$  TeV [22].

Charm mesons produced at the  $pp$  collision point, either directly or as decay products of excited charm resonances, are referred to as promptly produced. No attempt is made to distinguish between these two sources. This paper presents measurements of the cross-sections for the prompt production of  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^*(2010)^+$  (henceforth denoted as  $D^{*+}$ ) mesons, based on data corresponding to an integrated luminosity of  $8.60 \pm 0.33$  pb $^{-1}$ . Charm mesons produced through the decays of  $b$  hadrons are referred to as secondary charm and are considered here as a background process.

The analysis techniques described in this paper are nearly identical to those used in the measurements made at  $\sqrt{s} = 13$  TeV [22], allowing for very precise determination of the ratios between the two results.

Section 2 describes the detector, data acquisition conditions, and the simulation; this is followed by a summary of the data analysis in section 3. The differential cross-section results are given in section 4 while section 5 presents the measurements of integrated cross-sections and of the ratios of the cross-sections measured at  $\sqrt{s} = 5$  TeV to those at 13 TeV. The theoretical predictions and their comparison with the results of this paper are discussed in section 6. Section 7 provides a summary.

## 2 Detector and simulation

The LHCb detector [23, 24] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The tracking system provides a measurement of momentum of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ $c$ . The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is the component of the momentum transverse to the beam, in GeV/ $c$ . Different types of charged hadrons are distinguished by information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection is performed by a trigger. This consists of a hardware stage, which, for this analysis, randomly selects a pre-defined fraction of all beam-beam crossings at a rate of 300 kHz, followed by a software stage. In between the hardware and software stages, an alignment and calibration of the detector is performed in near real-time [25] and updated constants are made available for the trigger. The same alignment and calibration information is propagated to the offline reconstruction, ensuring consistent and high-quality particle identification (PID) information between the trigger and offline software. The identical performance of the online and offline reconstruction offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger [26, 27], which the present analysis exploits. The storage of only the triggered candidates enables a reduction in the event size by an order of magnitude.

In the simulation,  $pp$  collisions are generated with PYTHIA 8.1 [28, 29] using a specific LHCb configuration similar to the one described in ref. [30]. Decays of hadronic particles are described by EVTGEN [31] in which final-state radiation is generated with PHOTOS [32]. The implementation of the interaction of the generated particles with the detector, and its response, uses the GEANT4 toolkit [33, 34] as described in ref. [35].

## 3 Analysis strategy

The analysis methodology is very similar to that used to measure the prompt production cross-sections at  $\sqrt{s} = 13 \text{ TeV}$  [22], of which a summary is given below. The measurement at  $\sqrt{s} = 5 \text{ TeV}$  reconstructs the same final states:  $D^0 \rightarrow K^- \pi^+$ ,  $D^+ \rightarrow K^- \pi^+ \pi^+$ ,  $D_s^+ \rightarrow (K^- K^+)_{\phi} \pi^+$  and  $D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+$ . Throughout this paper, charge conjugation is implied and thus the  $D^0 \rightarrow K^- \pi^+$  sample contains the sum of the Cabibbo-favoured decays  $D^0 \rightarrow K^- \pi^+$  and the doubly Cabibbo-suppressed decays  $\bar{D}^0 \rightarrow K^- \pi^+$ . The  $D_s^+ \rightarrow (K^- K^+)_{\phi} \pi^+$  sample comprises all reconstructed  $D_s^+ \rightarrow K^- K^+ \pi^+$  decays

where the invariant mass of the  $K^-K^+$  pair falls into a  $\pm 20 \text{ MeV}/c^2$  window around the nominal  $\phi(1020)$  mass, taken to be  $1020 \text{ MeV}/c^2$ .

The cross-sections are measured in two-dimensional bins of  $p_T$  and  $y$  of the reconstructed mesons, where  $p_T$  and  $y$  are measured in the  $pp$  centre-of-mass frame with respect to the  $pp$  collision axis. The bin widths are 0.5 in  $y$  covering a range of  $2.0 < y < 4.5$  and  $1 \text{ GeV}/c$  in  $p_T$  for  $0 < p_T < 10 \text{ GeV}/c$ .

### 3.1 Selection of candidates

Candidates for  $D^0$ ,  $D^+$  and  $D_s^+$  mesons are formed in events containing at least one reconstructed PV by combining tracks that have been positively identified as kaons or pions by the LHCb PID system. These tracks are required to be above a transverse momentum threshold that depends on the decay mode, and must be consistent with originating from a common vertex. Due to the long lifetimes of the studied charm mesons, this common vertex is required to be significantly displaced from any reconstructed PV and the displacement vector with respect to the closest PV must align with the combined momentum of the tracks. Candidates for  $D^{*+}$  mesons are formed by combining a  $D^0$  and a charged pion candidate, requiring that both form a good quality vertex. Applying the selection, 1% of all events have more than one selected candidate, all of which are considered in this analysis.

The efficiencies for the reconstruction and selection of charm meson candidates are obtained for each  $(p_T, y)$  bin in a near-identical manner to the  $\sqrt{s} = 13 \text{ TeV}$  measurement [22]. All efficiencies are evaluated using the event simulation, except for the efficiencies for identifying kaons and pions and the tracking efficiencies. Kaon and pion identification efficiencies are evaluated using a high purity calibration sample of  $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\pi^+$  decays which have been selected without PID requirements. Only the correct assignment of the kaon and pion hypotheses for the decay products of the  $D^0$  candidates yields the expected shapes in the mass distributions. The numbers of true kaon and pion tracks in the calibration sample are determined from maximum likelihood fits to the  $D^0$  and  $D^{*+}$  candidate invariant mass distributions, as described in section 3.2. The identification efficiency for a true kaon or pion to pass a given PID requirement is computed by performing these fits in bins of track multiplicity and track kinematics before and after the selection. This technique differs slightly from that used in the analysis of the  $\sqrt{s} = 13 \text{ TeV}$  data, where a single maximum likelihood fit was performed on the calibration sample integrated across all bins, and the per-bin kaon and pion yields were computed by summing sWeights [36]. The change leads to a stable solution for sparsely populated bins and is introduced due to the substantially smaller size of the calibration sample compared to the  $\sqrt{s} = 13 \text{ TeV}$  measurement. Tracking efficiencies in the simulation are corrected with a factor derived from data as described in ref. [37] with typical values in the range of 0.97 to 1.02.

### 3.2 Determination of signal yields

The data contain a mixture of prompt signal decays, secondary charm mesons produced in decays of  $b$  hadrons, and combinatorial background. While combinatorial background can be distinguished from signal decays in the invariant mass distribution of charm meson candidates, both prompt signal decays and secondary charm mesons have the same mass shape. However, secondary charm mesons will, on average, have a greater IP with respect

Hadron	Prompt signal yield
$D^0$	$(34.4 \pm 0.7) \times 10^4$
$D^+$	$(27.6 \pm 0.6) \times 10^4$
$D_s^+$	$(13.2 \pm 0.1) \times 10^3$
$D^{*+}$	$(39.0 \pm 0.2) \times 10^3$

**Table 1.** Prompt signal yields in the fully selected dataset, summed over all  $(p_T, y)$  bins in which a measurement is made. Only statistical uncertainties are given.

to the closest PV than prompt signal, and this is exploited by using the spectrum of  $\ln(\chi_{\text{IP}}^2)$  of the charm meson candidates, where  $\chi_{\text{IP}}^2$  is defined as the difference in  $\chi^2$  of the PV fit, performed with and without the particle under consideration.

The prompt signal yield in each  $(p_T, y)$  bin is obtained from a fit to the  $\ln(\chi_{\text{IP}}^2)$  distribution of the charm meson within a  $20 \text{ MeV}/c^2$  window around the known mass [38] of the  $D^0$ ,  $D^+$ , or  $D_s^+$  meson, corresponding to approximately 2.5 times the mass resolution. For the  $D^{*+}$  measurements, an additional signal window around the nominal  $\Delta m = m(D^{*+}) - m(D^0)$  value of  $145.43 \text{ MeV}/c^2$  [38] is used, and the fit is made to the  $\ln(\chi_{\text{IP}}^2)$  distribution of the  $D^0$  meson. Candidates outside the signal region are used to construct templates for the combinatorial background shape in the  $\ln(\chi_{\text{IP}}^2)$  distributions. For the  $D^0$ ,  $D^+$ , and  $D_s^+$  measurements, a fit to the invariant mass distributions is used to constrain the number of combinatorial background candidates in the  $\ln(\chi_{\text{IP}}^2)$  fit. A fit to the  $\Delta m$  distribution is used for the  $D^{*+}$  measurements. The fits to the invariant mass,  $\Delta m$ , and  $\ln(\chi_{\text{IP}}^2)$  distributions are performed as extended binned maximum likelihood fits, performed simultaneously across all  $(p_T, y)$  bins. The fit model definitions, and the choice of model parameters that are shared across  $(p_T, y)$  bins, are identical to those used in the  $\sqrt{s} = 13 \text{ TeV}$  measurement [22].

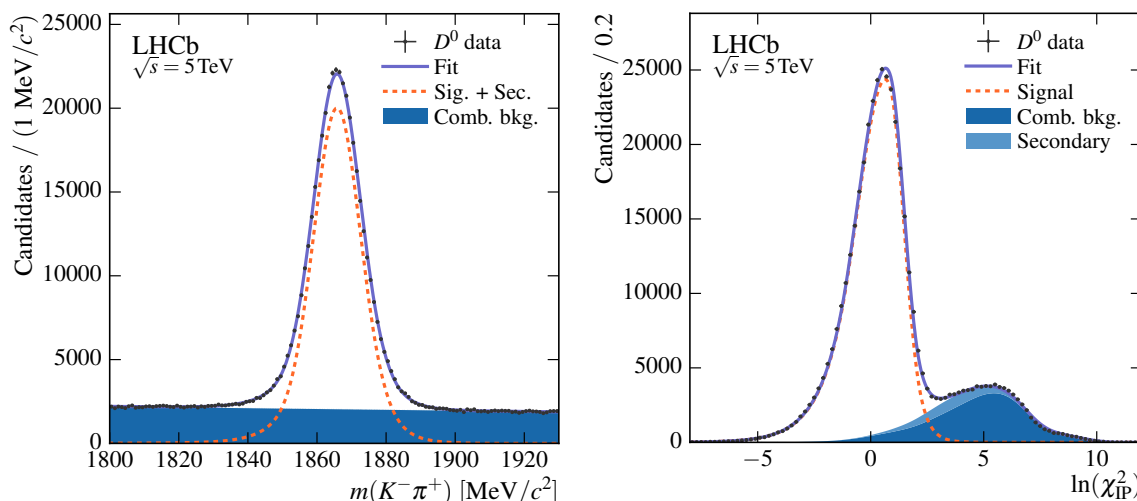
The sums of the fits over all  $(p_T, y)$  bins are given in figures 1–4. The fits generally describe the data well. Inaccuracies in the description of the data by the fit model are found to have only a small effect on the estimated prompt signal yield and are taken into account as systematic uncertainties. The sums of the prompt signal yields, as determined by the fits, are given in table 1.

## 4 Cross-section measurements

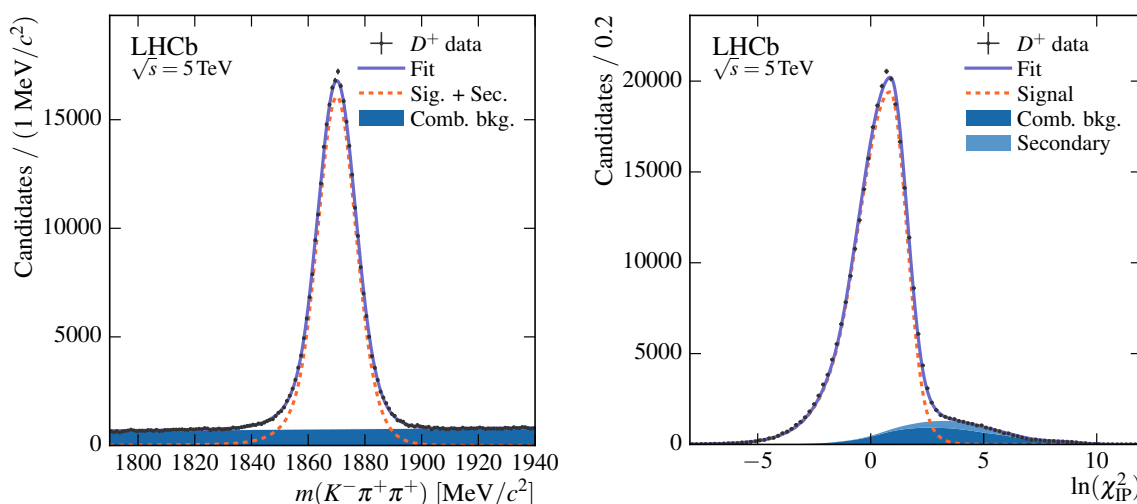
In each  $(p_T, y)$  bin  $i$ , the bin averaged differential cross-section for producing the charm meson  $D$  is calculated from the relation

$$\frac{d^2\sigma_i(D)}{dp_T dy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(D \rightarrow f + \text{c.c.})}{\varepsilon_{i,\text{tot}}(D \rightarrow f) \mathcal{B}(D \rightarrow f) \kappa \mathcal{L}_{\text{int}}}, \quad (4.1)$$

where  $\Delta p_T$  and  $\Delta y$  are the widths in  $p_T$  and  $y$  of bin  $i$ ,  $N_i(D \rightarrow f + \text{c.c.})$  is the measured yield of prompt  $D$  decays to the final state  $f$  in bin  $i$  from the  $\ln(\chi_{\text{IP}}^2)$  fit including the charge-conjugate decay, and  $\varepsilon_{i,\text{tot}}(D \rightarrow f)$  is the total efficiency for observing the signal



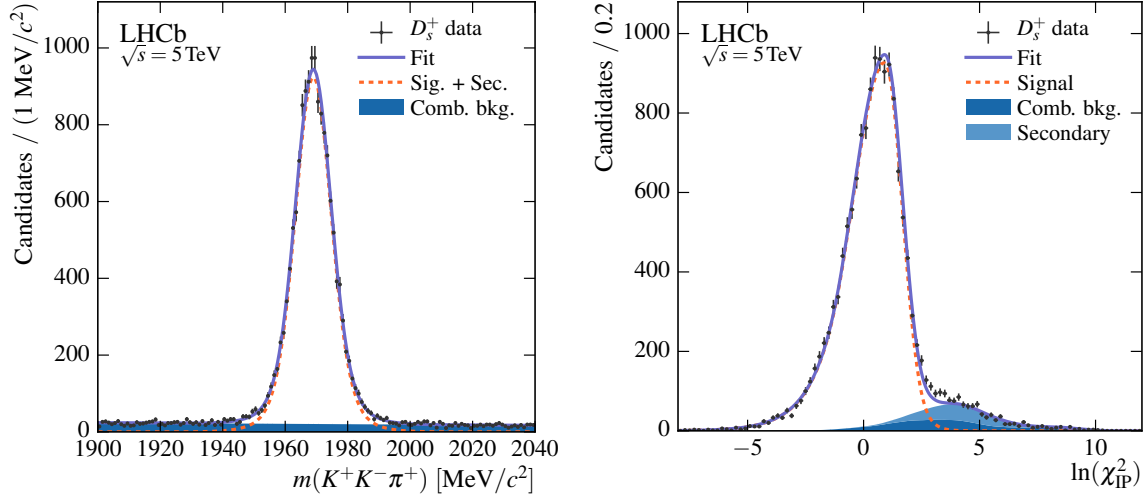
**Figure 1.** Distributions for selected  $D^0 \rightarrow K^- \pi^+$  candidates: (left)  $K^- \pi^+$  invariant mass and (right)  $\ln(\chi^2_{\text{IP}})$  for a mass window of  $\pm 20 \text{ MeV}/c^2$  around the nominal  $D^0$  mass. The sum of the simultaneous likelihood fits in each  $(p_T, y)$  bin is shown, with components as indicated in the legends.



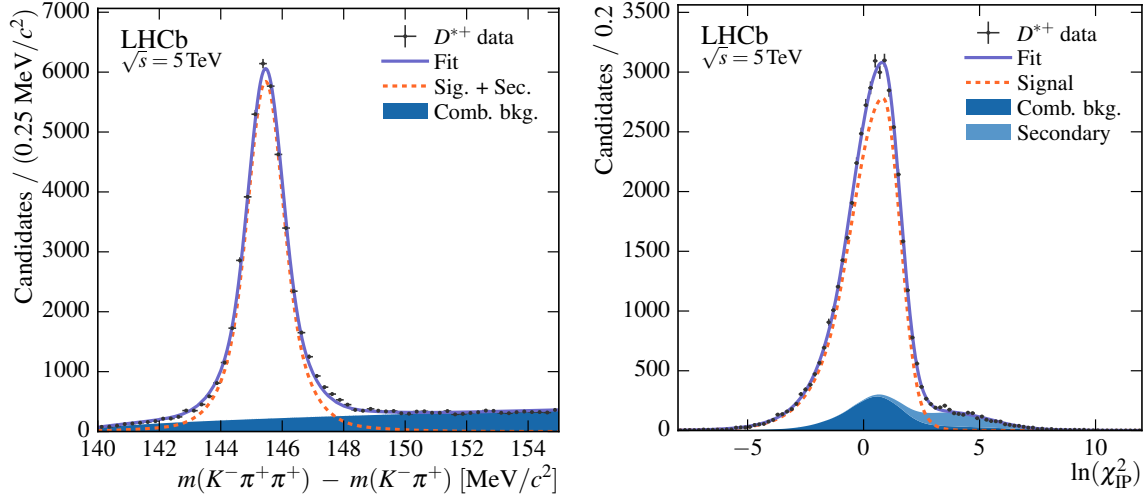
**Figure 2.** Distributions for selected  $D^+ \rightarrow K^- \pi^+ \pi^+$  candidates: (left)  $K^- \pi^+ \pi^+$  invariant mass and (right)  $\ln(\chi^2_{\text{IP}})$  for a mass window of  $\pm 20 \text{ MeV}/c^2$  around the nominal  $D^+$  mass. The sum of the simultaneous likelihood fits in each  $(p_T, y)$  bin is shown, with components as indicated in the legends.

decay in bin  $i$ . The total integrated luminosity collected,  $\mathcal{L}_{\text{int}}$ , is  $8.60 \pm 0.33 \text{ pb}^{-1}$  and  $\kappa = 1.86\%$  is the efficiency of the hardware trigger. The integrated luminosity of the dataset is evaluated from the number of visible  $pp$  collisions and a constant of proportionality that is measured in a dedicated calibration dataset. The absolute luminosity for the calibration dataset is determined from the beam currents, which are measured by LHC instruments, and the beam profiles and overlap integral, which are measured with a beam-gas imaging method [39]. In contrast to ref. [39], no van der Meer scan is used. The correlation





**Figure 3.** Distributions for selected  $D_s^+ \rightarrow (K^- K^+) \phi \pi^+$  candidates: (left)  $K^+ K^- \pi^+$  invariant mass and (right)  $\ln(\chi_{\text{IP}}^2)$  for a mass window of  $\pm 20 \text{ MeV}/c^2$  around the nominal  $D_s^+$  mass. The sum of the simultaneous likelihood fits in each  $(p_T, y)$  bin is shown, with components as indicated in the legends.



**Figure 4.** Distributions for selected  $D^{*+} \rightarrow D^0 \pi^+$  candidates, with  $D^0 \rightarrow K^- \pi^+$ : (left)  $\Delta m = m(D^{*+}) - m(D^0)$  for a mass window of  $\pm 20 \text{ MeV}/c^2$  around the nominal  $D^0$  mass and (right)  $\ln(\chi_{\text{IP}}^2)$  of the  $D^0$  with an additional mass window of  $\pm 3 \text{ MeV}/c^2$  around the nominal  $D^{*+} - D^0$  mass difference. The sum of the simultaneous likelihood fits in each  $(p_T, y)$  bin is shown, with components as indicated in the legends.

	Uncertainties (%)				Correlations (%)	
	$D^0$	$D^+$	$D_s^+$	$D^{*+}$	Bins	Decay modes
Luminosity			3.8		100	100
Tracking	3–5	5–7	4–7	5–7	90–100	90–100
Branching fractions	1.2	2.1	5.8	1.5	100	0–95
Simulation sample size	0–10	0–10	2–9	1–10	0	0
Simulation modelling	0.3	0.7	0.6	2	0	0
PID sample size	0–1	0–1	0–2	0–2	0–100	0–100
PID binning	0–30	0–10	0–20	0–20	0	0
Fit model shapes	0–3	0–3	0–3	0.0–1.0	0	0

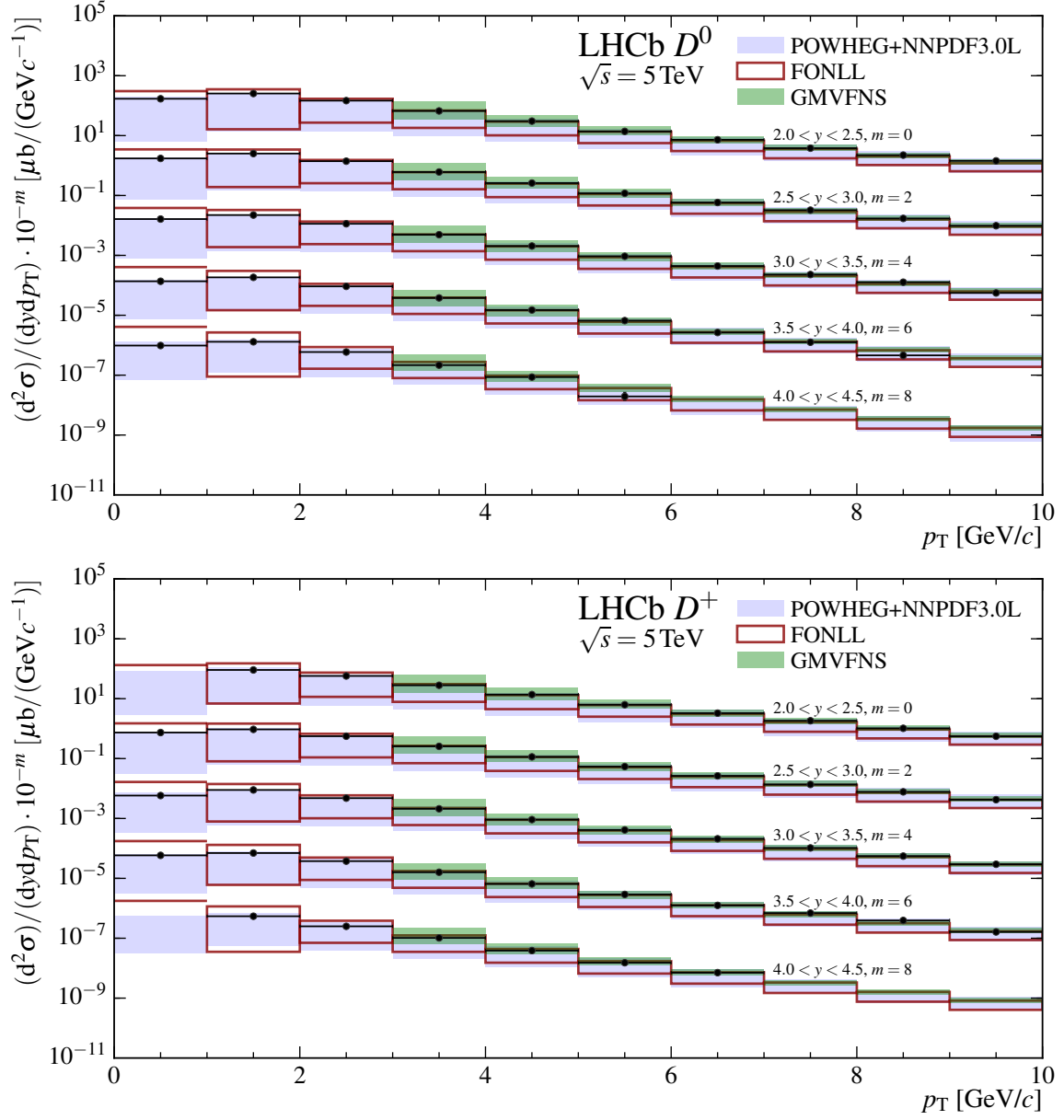
**Table 2.** Fractional systematic uncertainties, in percent. Uncertainties that are computed bin-by-bin are expressed as ranges giving the minimum to maximum values. Ranges for the correlations between  $p_T$ - $y$  bins and between modes are also given, expressed in percent.

coefficient between the uncertainties of the luminosity measurements at  $\sqrt{s} = 5$  TeV and  $\sqrt{s} = 13$  TeV is 32%.

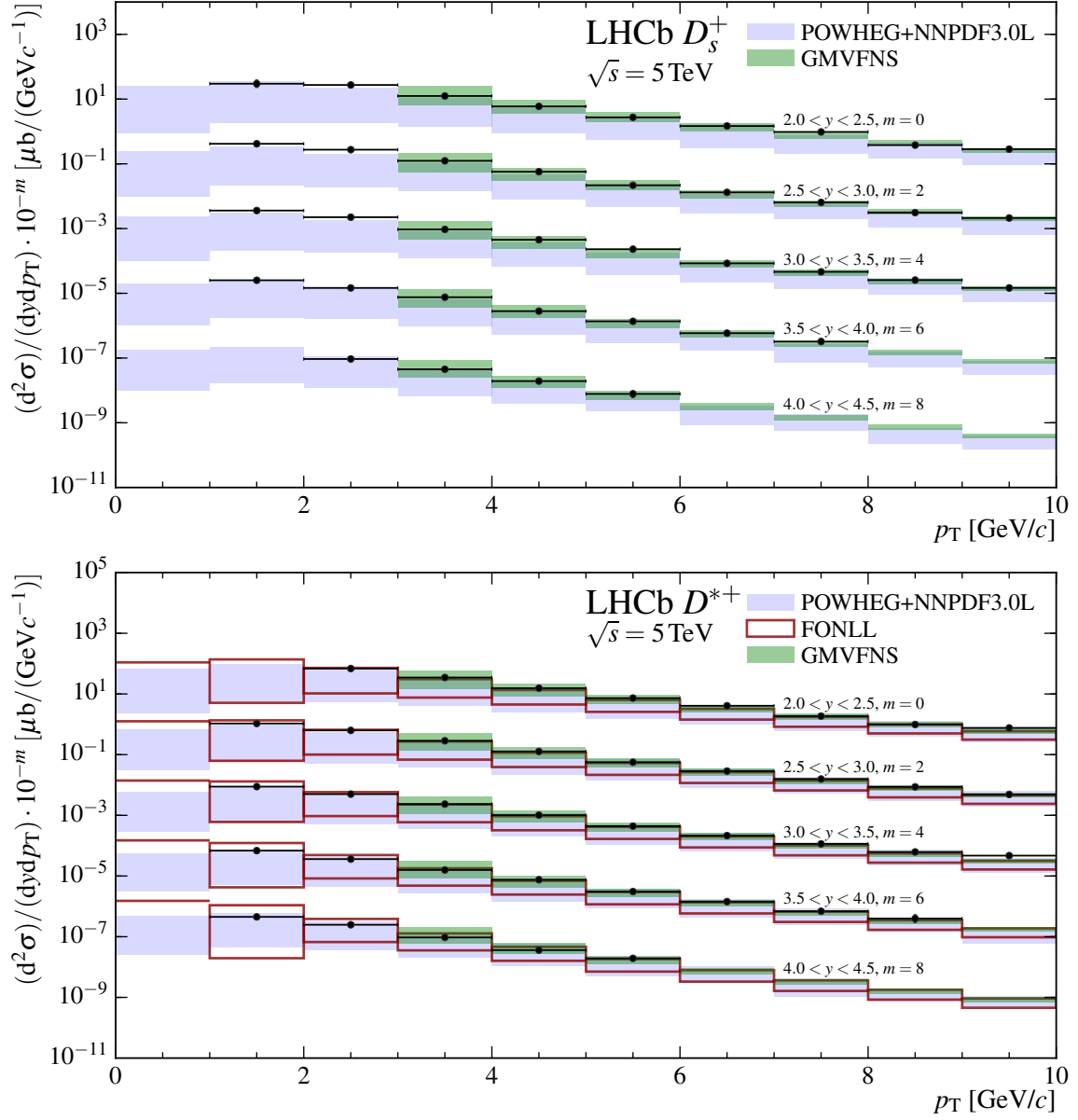
The values for the branching fractions, taken from ref. [38], are identical to those used in the  $\sqrt{s} = 13$  TeV measurement [22], thus ensuring a complete cancellation in ratios between cross-sections measured at 13 and 5 TeV. The values  $\mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+)$ ,  $\mathcal{B}(D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+)$ , and  $\mathcal{B}(D^0 \rightarrow K^\mp \pi^\pm)$  are  $(9.13 \pm 0.19)\%$ ,  $(2.63 \pm 0.04)\%$ , and  $(3.89 \pm 0.05)\%$ , respectively. For the  $D_s^+$  measurement the fraction of  $D_s^+ \rightarrow K^- K^+ \pi^+$  decays with a  $K^- K^+$  invariant mass in the range  $1000 < m_{K^- K^+} < 1040$  MeV/ $c^2$  is taken as  $(2.24 \pm 0.13)\%$  [40].

Several sources of systematic uncertainty are identified and evaluated for each decay mode and  $(p_T, y)$  bin as described in ref. [22]. For all decay modes, the dominant uncertainties in most bins are due to the luminosity and the estimation of the tracking efficiencies. The calibration of the tracking efficiencies is performed independently for datasets taken at different centre-of-mass energies, leading to different relative uncertainties compared to the  $\sqrt{s} = 13$  TeV analysis. The simulated sample gives rise to systematic uncertainties due to its finite size and imperfect modelling of the selection variables. Uncertainties are also evaluated for the PID calibration procedure to account for the finite size of the calibration sample and residual differences of the kinematic distributions between the calibration sample and the final state tracks. Additionally, an uncertainty is evaluated to account for the choice of fit models used in the determination of the signal yields. Table 2 lists the fractional systematic uncertainties for the different decay modes and their correlations between different  $(p_T, y)$  bins and decay modes.

The measured differential cross-sections are tabulated in appendix A. Figures 5 and 6 show the  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^{*+}$  cross-section measurements and predictions [1–3], which are discussed in section 6.



**Figure 5.** Measurements and predictions for the absolute prompt (top)  $D^0$ , and (bottom)  $D^+$  cross-sections at  $\sqrt{s} = 5 \text{ TeV}$ . Each set of measurements and predictions in a given rapidity bin is offset by a multiplicative factor  $10^{-m}$ , where the factor  $m$  is shown on the plots. The boxes indicate the  $\pm 1\sigma$  uncertainty band on the theory predictions, where only the upper edge is shown if the uncertainty exceeds two orders of magnitude.



**Figure 6.** Measurements and predictions for the absolute prompt (top)  $D_s^+$ , and (bottom)  $D^{*+}$  cross-sections at  $\sqrt{s} = 5$  TeV. Each set of measurements and predictions in a given rapidity bin is offset by a multiplicative factor  $10^{-m}$ , where the factor  $m$  is shown on the plots. The boxes indicate the  $\pm 1\sigma$  uncertainty band on the theory predictions, where only the upper edge is shown if the uncertainty exceeds two orders of magnitude.

## 5 Production ratios and integrated cross-sections

### 5.1 Production ratios

The present analysis uses the same techniques as the LHCb measurement at  $\sqrt{s} = 13$  TeV. Therefore, several sources of systematic uncertainty are highly correlated, leading to cross-section ratios between  $\sqrt{s} = 13$  TeV and  $\sqrt{s} = 5$  TeV,  $R_{13/5}$ , with greatly reduced relative uncertainties compared to the differential cross-sections. Furthermore, the predicted ratios of prompt charm production cross-sections between different centre-of-mass energies have cancellations of several theoretical uncertainties [1–3]. The  $\sqrt{s} = 13$  TeV measurements are rebinned to match the binning used for the present results and the production ratios are presented for  $0 < p_T < 8$  GeV/c and  $2.0 < y < 4.5$  in appendix B. Figure 7 shows the measured ratios for  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^{*+}$  mesons compared with predictions from theory calculations [1–3], discussed in section 6.

A second set of differential ratios is obtained by dividing the prompt charm production cross-sections of different charm mesons. These can be compared with the ratios of the cross-sections measured at  $e^+e^-$  colliders operating at a centre-of-mass energy close to the  $\Upsilon(4S)$  resonance [41–43]. Those measurements were performed with the same final states as the analysis presented here. Therefore, a more precise comparison is made by taking ratios of  $\sigma(D) \times \mathcal{B}(D \rightarrow f)$ . Differential ratios are shown in figures 8 and 9, and tabulated results are presented in appendix C. The measurements in each  $p_T$  bin are shown integrated over  $y$  for clearer visualisation. They exhibit a  $p_T$  dependence that is consistent with heavier particles having a harder  $p_T$  spectrum.

### 5.2 Integrated cross-sections

Integrated production cross-sections,  $\sigma(D)$ , for each charm meson are computed as the sum of the measurements in each bin, where the uncertainty on the sum takes into account the correlations between bins. Integrated cross-sections are computed for all four mesons in the kinematic region  $1 < p_T < 8$  GeV/c and  $2.0 < y < 4.5$  and additionally down to  $p_T = 0$  GeV/c for  $D^0$  and  $D^+$ . The upper limit of  $p_T = 8$  GeV/c is chosen to match that of the measurements at  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 13$  TeV.

Contributions from bins within the integration range for which a measurement was not possible are estimated using a theory-based correction factor, computed as the ratio between the predicted integrated cross-section within the considered kinematic region and the sum of all cross-section predictions for bins for which a measurement exists, as in ref. [22]. POWHEG+NNPDF3.0L [1] predictions, discussed in the next section, are used to compute the extrapolation factor. From the differences between the central value and the upper and lower bounds on the prediction, the larger of the two is assigned as systematic uncertainty of the extrapolation factor. Table 3 gives the integrated cross-sections for  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^{*+}$  mesons and table 4 gives the corresponding values for the ratios of integrated cross-sections measured at  $\sqrt{s} = 13$  TeV and 5 TeV.

The integrated  $c\bar{c}$  production cross-section,  $\sigma(pp \rightarrow c\bar{c}X)$ , is calculated as  $\sigma(D)/(2f(c \rightarrow D))$  for each decay mode. The term  $f(c \rightarrow D)$  is the quark-to-hadron tran-

			Extrapolation factor	Cross-section ( $\mu\text{b}$ )
$D^0$	$0 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$	$1.0013 \pm 0.0019$	$1374 \pm 3 \pm 74$
$D^+$	$0 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$	$1.108 \pm 0.049$	$551 \pm 5 \pm 48$
$D^0$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$	$1.0017 \pm 0.0020$	$1004 \pm 3 \pm 54$
$D^+$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$	$1.00062 \pm 0.00099$	$402 \pm 2 \pm 30$
$D_s^+$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$	$1.0734 \pm 0.0080$	$170 \pm 4 \pm 16$
$D^{*+}$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$	$1.122 \pm 0.046$	$421 \pm 5 \pm 36$
$D^0$	$0 < p_T < 8 \text{ GeV}/c$	$2.5 < y < 4$	—	$866 \pm 2 \pm 45$
$D^+$	$0 < p_T < 8 \text{ GeV}/c$	$2.5 < y < 4$	—	$349 \pm 4 \pm 27$
$D^0$	$1 < p_T < 8 \text{ GeV}/c$	$2.5 < y < 4$	—	$630 \pm 2 \pm 33$
$D^+$	$1 < p_T < 8 \text{ GeV}/c$	$2.5 < y < 4$	—	$253 \pm 1 \pm 18$
$D_s^+$	$1 < p_T < 8 \text{ GeV}/c$	$2.5 < y < 4$	—	$110 \pm 2 \pm 10$
$D^{*+}$	$1 < p_T < 8 \text{ GeV}/c$	$2.5 < y < 4$	—	$267 \pm 3 \pm 21$

**Table 3.** Prompt  $D$ -meson production cross-sections in the kinematic ranges given. The computation of the extrapolation factors is described in ref. [22]. The first uncertainty on the cross-section is statistical, and the second is systematic and includes the contribution from the extrapolation factor. A dash indicates that measurements are available in all bins and no extrapolation factor is needed. Integrated numbers in the reduced acceptance  $2.5 < y < 4.0$  are quoted as reference for future heavy ion measurements.

sition probability, and the factor 2 accounts for the inclusion of charge-conjugate states in the measurement. Measurements at  $e^+e^-$  colliders operating at a centre-of-mass energy close to the  $\Upsilon(4S)$  resonance are used to determine the transition probabilities [44]  $f(c \rightarrow D^0) = 0.565 \pm 0.032$ ,  $f(c \rightarrow D^+) = 0.246 \pm 0.020$ ,  $f(c \rightarrow D_s^+) = 0.080 \pm 0.017$ , and  $f(c \rightarrow D^{*+}) = 0.224 \pm 0.028$ . The fragmentation fraction  $f(c \rightarrow D^0)$  has an overlapping contribution from  $f(c \rightarrow D^{*+})$ .

The combination of the individual  $D^0$  and  $D^+$  measurements of the  $c\bar{c}$  cross-section is performed by means of a weighted average that minimises the variance of the estimate [45], giving

$$\sigma(pp \rightarrow c\bar{c}X)_{p_T < 8 \text{ GeV}/c, 2.0 < y < 4.5} = 1193 \pm 3 \pm 67 \pm 58 \mu\text{b},$$

where the uncertainties are due to statistical, systematic and fragmentation fraction uncertainties, respectively. The specified kinematic range refers to the produced charm hadron, not the individual charm quarks. A comparison with predictions is given in figure 10. The same figure also shows a comparison of  $\sigma(pp \rightarrow c\bar{c}X)$  for  $1 < p_T < 8 \text{ GeV}/c$  based on the measurements of the four meson species. Ratios of the integrated measurements of cross-section times branching fraction are given in table 5.

				$R_{13/5}$		
$D^0$	$0 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$		$1.977 \pm 0.005 \pm 0.120$		
$D^+$	$0 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$		$2.02 \pm 0.02 \pm 0.22$		
$D^0$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$		$2.070 \pm 0.006 \pm 0.121$		
$D^+$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$		$2.09 \pm 0.01 \pm 0.19$		
$D_s^+$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$		$2.09 \pm 0.07 \pm 0.23$		
$D^{*+}$	$1 < p_T < 8 \text{ GeV}/c$	$2 < y < 4.5$		$1.87 \pm 0.03 \pm 0.23$		

**Table 4.** Ratios of integrated prompt  $D$ -meson production cross-sections between measurements at  $\sqrt{s} = 13 \text{ TeV}$  and  $\sqrt{s} = 5 \text{ TeV}$ . The first uncertainty on the ratio is statistical, and the second is systematic.

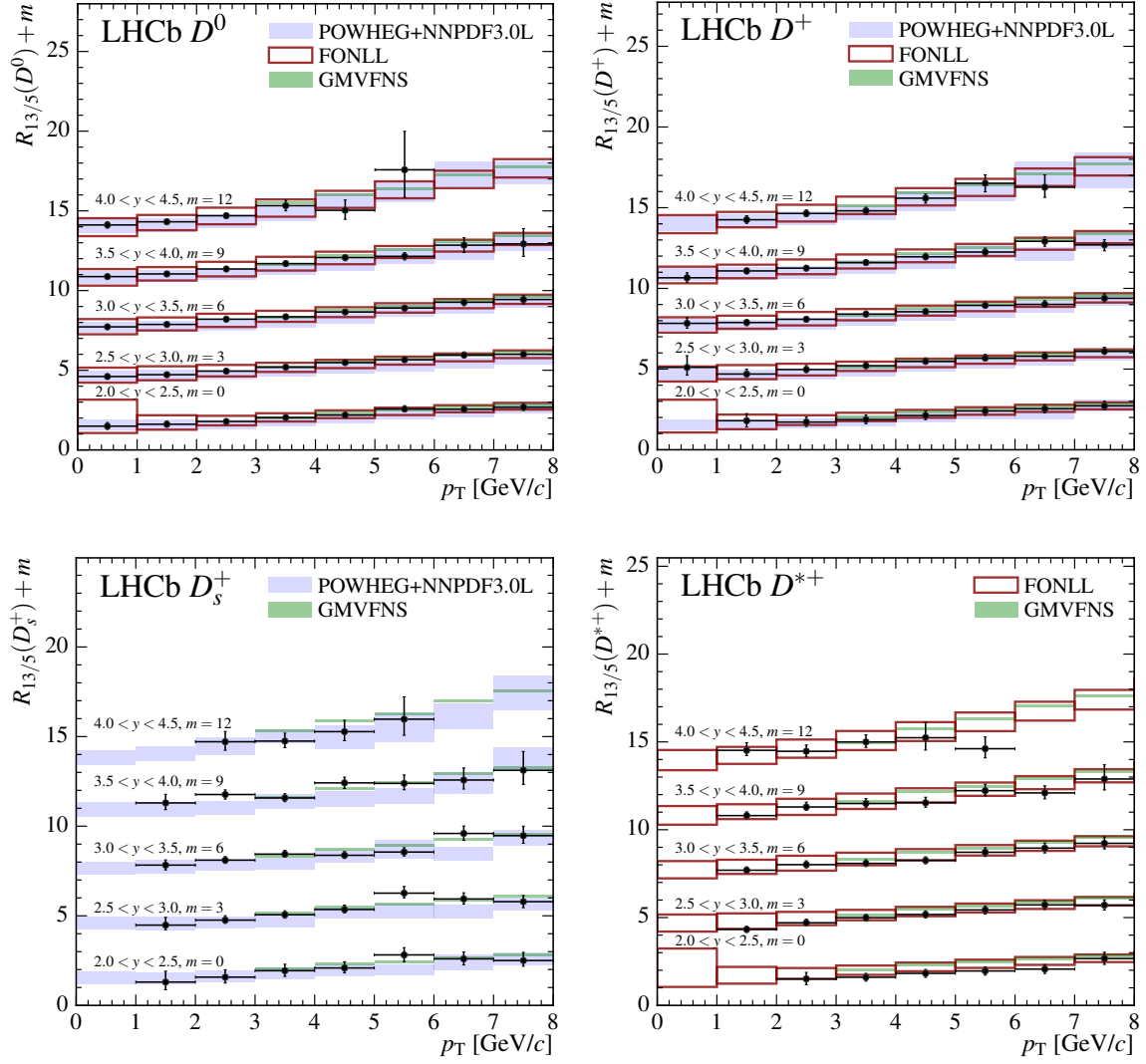
Quantity	Measurement
$\sigma(D^+ \rightarrow K^- \pi^+ \pi^+)/\sigma(D^0 \rightarrow K^- \pi^+)$	$0.943_{-0.005}^{+0.005} \pm 0.029$
$\sigma(D_s^+ \rightarrow [K^- K^+]_{\phi} \pi^+)/\sigma(D^0 \rightarrow K^- \pi^+)$	$0.0983_{-0.0021}^{+0.0021} \pm 0.0035$
$\sigma(D^{*+} \rightarrow [K^- \pi^+]_{D^0} \pi^+)/\sigma(D^0 \rightarrow K^- \pi^+)$	$0.283_{-0.004}^{+0.004} \pm 0.016$
$\sigma(D_s^+ \rightarrow [K^- K^+]_{\phi} \pi^+)/\sigma(D^+ \rightarrow K^- \pi^+ \pi^+)$	$0.1042_{-0.0022}^{+0.0022} \pm 0.0031$
$\sigma(D^{*+} \rightarrow [K^- \pi^+]_{D^0} \pi^+)/\sigma(D^+ \rightarrow K^- \pi^+ \pi^+)$	$0.300_{-0.004}^{+0.004} \pm 0.015$
$\sigma(D_s^+ \rightarrow [K^- K^+]_{\phi} \pi^+)/\sigma(D^{*+} \rightarrow [K^- \pi^+]_{D^0} \pi^+)$	$0.348_{-0.009}^{+0.008} \pm 0.018$

**Table 5.** Ratios of the measurements of cross-section times branching fraction in the kinematic range  $1 < p_T < 8 \text{ GeV}/c$  and  $2 < y < 4.5$ . The first uncertainty on the ratio is statistical and the second is systematic. The notation  $\sigma(D \rightarrow f)$  is shorthand for  $\sigma(D) \times \mathcal{B}(D \rightarrow f)$ .

## 6 Comparison to theory

Theoretical calculations for charm meson production cross-sections in  $pp$  collisions at  $\sqrt{s} = 5 \text{ TeV}$ , according to the same methods described in refs. [1] (POWHEG+NNPDF3.0L), [2] (FONLL) and [3] (GMVFNS), have been provided by the authors. All sets of calculations are performed at NLO precision, and each includes estimates of theoretical uncertainties due to the renormalisation and factorisation scales. The theoretical uncertainties provided with the POWHEG+NNPDF3.0L predictions also include contributions due to uncertainties in the effective charm quark mass and the parton distribution functions.

The FONLL predictions are provided in the form of  $D^0$ ,  $D^+$ , and  $D^{*+}$  production cross-sections for  $pp$  collisions at  $\sqrt{s} = 5 \text{ TeV}$  for each phase space bin in the range  $p_T < 10 \text{ GeV}/c$  and  $2.0 < y < 4.5$ . Ratios of these cross-sections to those computed for  $pp$  collisions at 13 TeV are also supplied. The calculations use the NNPDF3.0 NLO [46] parton densities. These FONLL calculations of the meson differential production cross-sections assume  $f(c \rightarrow D) = 1$  and are multiplied by the transition probabilities measured at  $e^+e^-$  col-

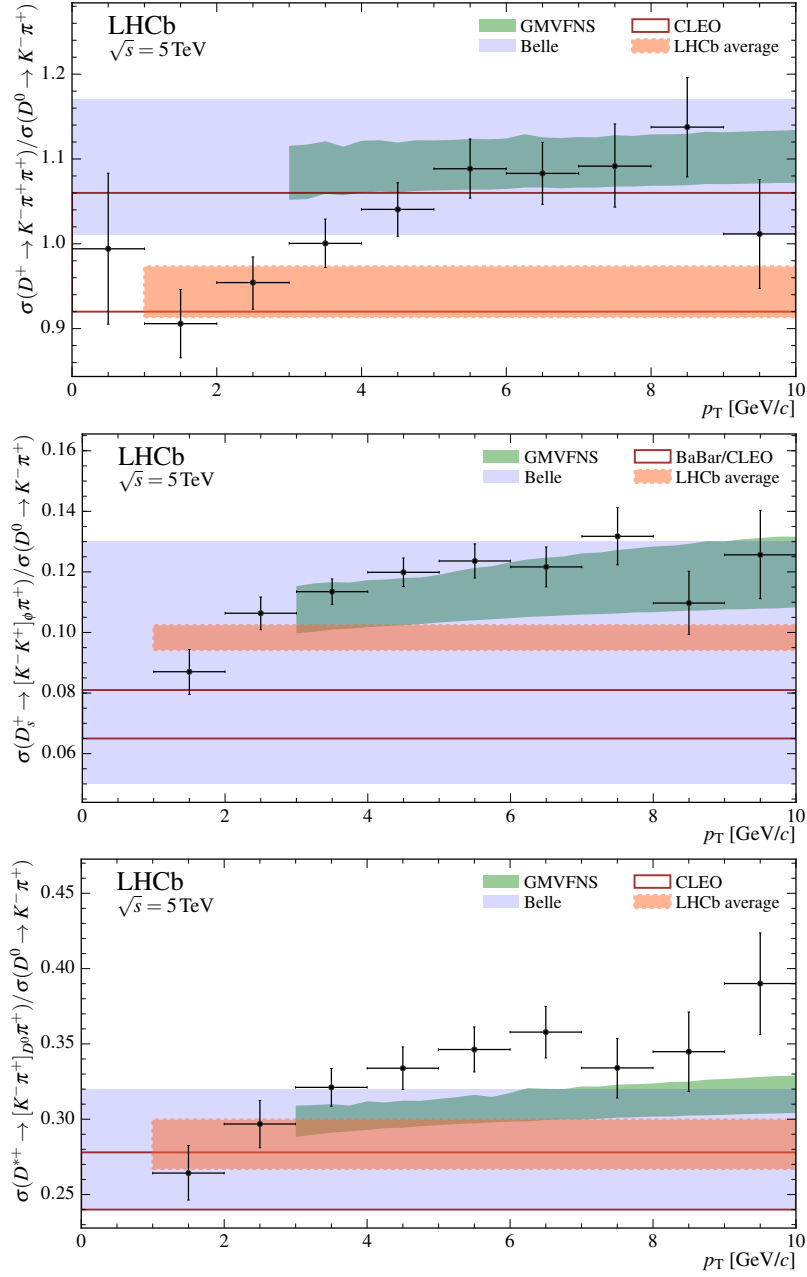


**Figure 7.** Measurements and predictions of the prompt  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^{*+}$  cross-section ratios between  $\sqrt{s} = 13$  and 5 TeV. Each set of measurements and predictions in a given rapidity bin is offset by an additive constant  $m$ , which is shown on the plot. Only central values are provided for the GMVFNS predictions.

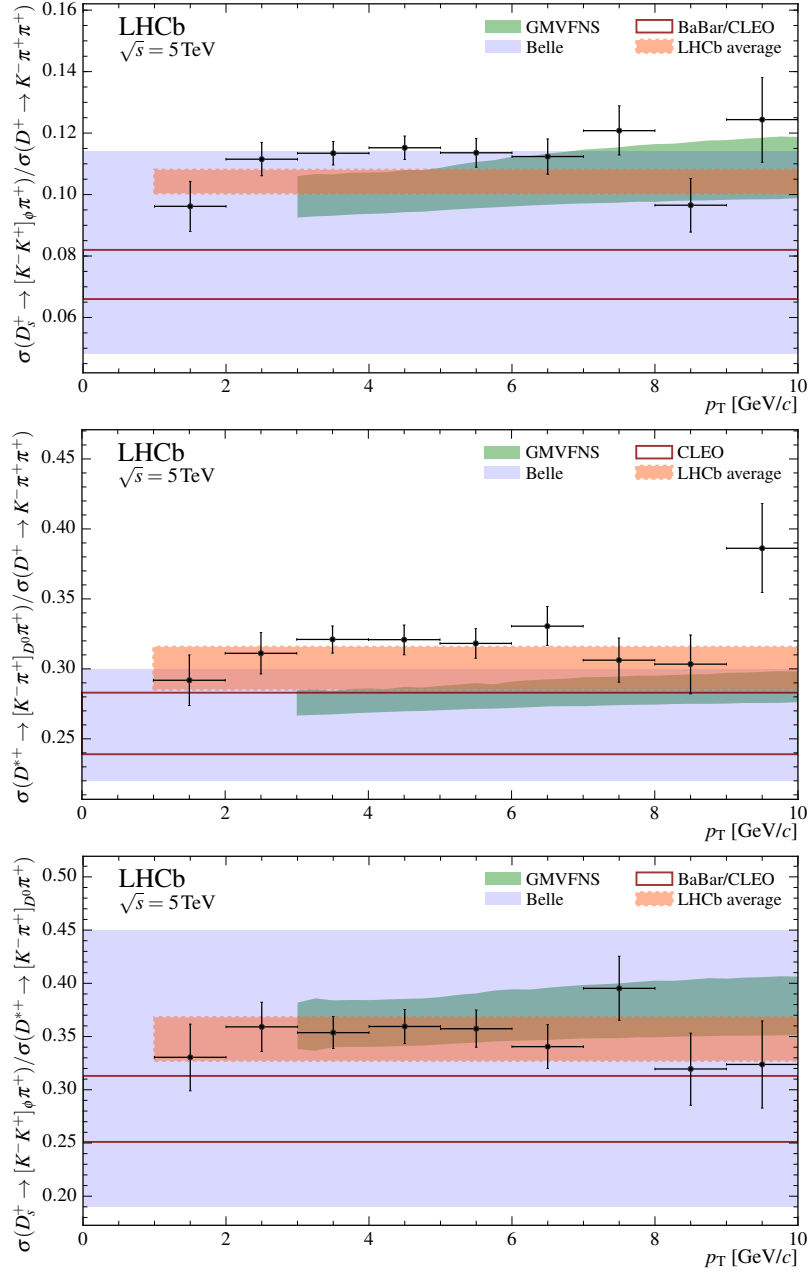
leaders for comparison to the current measurements. No dedicated FONLL cross-section calculation for  $D_s^+$  production is available.

The POWHEG+NNPDF3.0L predictions provide  $D^0$ ,  $D^+$ , and  $D_s^+$  integrated production cross-sections for  $pp$  collisions at  $\sqrt{s} = 5$  TeV in the same  $p_T$  and  $y$  binning used for the measurement. Ratios of  $\sqrt{s} = 13$  TeV to 5 TeV cross-sections are also predicted for  $D^0$ ,  $D^+$  and  $D_s^+$ . They are obtained with POWHEG [47] matched to PYTHIA8 [48] parton showers and an improved version of the NNPDF3.0 NLO parton distribution function set designated NNPDF3.0+LHCb [1]. To produce this improved set, the authors of ref. [1] weight the NNPDF3.0 NLO set in order to match FONLL calculations to the LHCb charm cross-section measurements at 7 TeV [21]. This results in a significant reduction in the un-

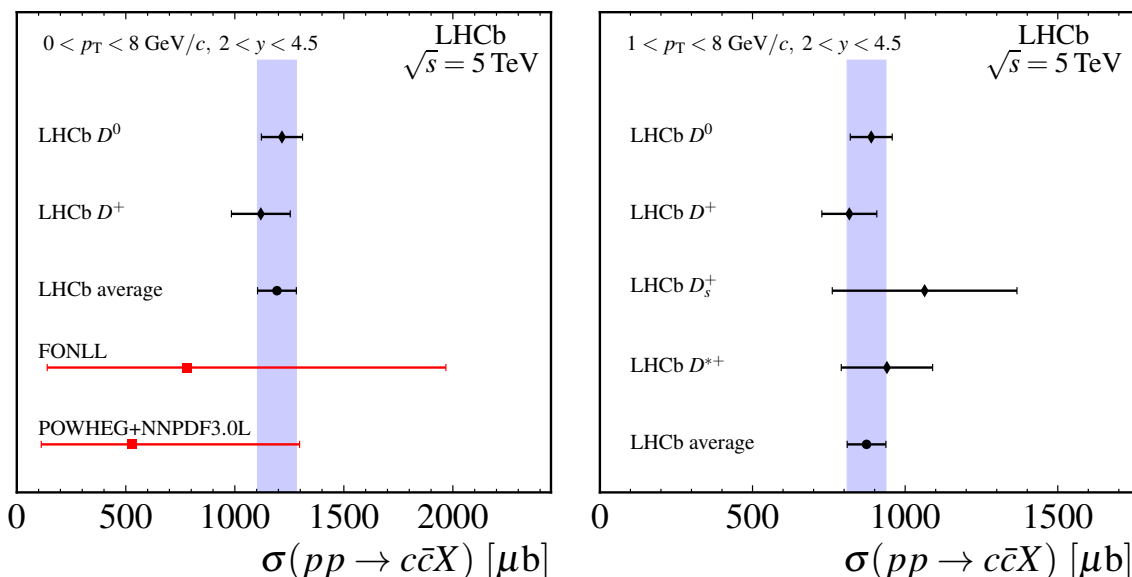




**Figure 8.** Ratios of the measurements of cross-section times branching fraction of (top)  $D^+$ , (middle)  $D_s^+$ , and (bottom)  $D^{*+}$  mesons with respect to the  $D^0$  measurements. The bands indicate the corresponding ratios computed using measurements from  $e^+e^-$  collider experiments [41–43]. The ratios are given as a function of  $p_T$  integrated over  $y$ . The notation  $\sigma(D \rightarrow f)$  is shorthand for  $\sigma(D) \times \mathcal{B}(D \rightarrow f)$ .



**Figure 9.** Ratios of the measurements of cross-section times branching fraction of (top)  $D^{*+}$ , and (middle)  $D_s^+$  mesons with respect to  $D^+$  cross-sections, and (bottom)  $D_s^+$  over  $D^{*+}$  mesons. The bands indicate the corresponding ratios computed using measurements from  $e^+e^-$  collider experiments [41–43]. The ratios are given as a function of  $p_T$  integrated over  $y$ . The notation  $\sigma(D \rightarrow f)$  is shorthand for  $\sigma(D) \times \mathcal{B}(D \rightarrow f)$ .



**Figure 10.** Integrated  $c\bar{c}$  cross-sections (black diamonds), their average (black circle and blue band) and theory predictions (red squares) [1, 2] are shown (left) based on the  $D^0$  and  $D^+$  for  $0 < p_T < 8 \text{ GeV}/c$  and (right) for measurements based on all four mesons for  $1 < p_T < 8 \text{ GeV}/c$ .

certainties for the gluon distribution function at small momentum fraction  $x$ . Predictions for the integrated cross-section are provided for each meson.

The GMVFNS calculations include theoretical predictions for the absolute cross-sections for all mesons studied in this analysis. Predictions of central values are also provided for the cross-section ratios between mesons. Results are provided for  $3 < p_T < 10 \text{ GeV}/c$ . Here the CT10 [49] set of parton distributions is used. The GMVFNS theoretical framework includes the convolution with fragmentation functions describing the transition  $c \rightarrow D$  that are normalised to the respective total transition probabilities [8, 50]. The fragmentation functions are taken from a fit to production measurements at  $e^+e^-$  colliders, where no attempt is made to separate direct production and feed-down from higher resonances.

In general, the predicted shapes of the cross-sections at  $\sqrt{s} = 5 \text{ TeV}$  agree with the data shown in figures 5 and 6. The central values of the measurements generally lie above those of the theory predictions, albeit within the uncertainties provided. For the POWHEG+NNPDF3.0L and FONLL predictions, the data tend to lie at the upper edge of the uncertainty band. The GMVFNS predictions provide a better description of the data, although the cross-sections decrease with  $p_T$  at a higher rate than the data near their low  $p_T$  limit of  $3 \text{ GeV}/c$ . Similar behaviour was observed for the  $\sqrt{s} = 7 \text{ TeV}$  measurement [21], where only central values were shown for the FONLL prediction, and for the  $\sqrt{s} = 13 \text{ TeV}$  measurement [22], where in both cases the predictions gave lower cross-sections than the data.

The data generally agree well with the FONLL, POWHEG+NNPDF3.0L and GMVFNS predictions for the ratios of cross-sections at  $\sqrt{s} = 13 \text{ TeV}$  and  $5 \text{ TeV}$ , shown in figure 7. These ratio measurements are significantly more precise than those previ-

ously presented between cross-sections at  $\sqrt{s} = 13$  TeV and 7 TeV, and will act as stronger constraints in PDF fits as a result.

## 7 Summary

A measurement of charm production in  $pp$  collisions at a centre-of-mass energy of  $\sqrt{s} = 5$  TeV has been performed with data collected with the LHCb detector. While the shapes of the differential cross-sections for  $D^0$ ,  $D^+$ ,  $D_s^+$ , and  $D^{*+}$  mesons are found to be in agreement with NLO perturbative QCD calculations, the measured values tend to lie at the upper edge of the predictions. This is a feature also common to the measurements at  $\sqrt{s} = 7$  and 13 TeV, which indicates a general underestimation in the prediction of the absolute value of prompt charm production in the forward region. The ratios of the production cross-sections for centre-of-mass energies of 13 TeV and 5 TeV have been measured and show consistency with theoretical predictions. The integrated cross-sections for prompt open charm meson production in  $pp$  collisions at  $\sqrt{s} = 5$  TeV and in the range  $1 < p_T < 8$  GeV/ $c$  and  $2 < y < 4.5$  are

$$\begin{aligned}\sigma(pp \rightarrow D^0 X) &= 1004 \pm 3 \pm 54 \mu\text{b}, \\ \sigma(pp \rightarrow D^+ X) &= 402 \pm 2 \pm 30 \mu\text{b}, \\ \sigma(pp \rightarrow D_s^+ X) &= 170 \pm 4 \pm 16 \mu\text{b}, \\ \sigma(pp \rightarrow D^{*+} X) &= 421 \pm 5 \pm 36 \mu\text{b}.\end{aligned}$$

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## A Absolute cross-sections

Tables 6–9 give the numerical results for the differential cross-sections.

$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[0, 1]	$170^{+3}_{-3} \pm 19^{+17}_{-17}$	$173^{+1}_{-1} \pm 10^{+10}_{-10}$	$163.1^{+1.3}_{-1.3} \pm 8.6^{+9.2}_{-9.2}$	$136.5^{+1.5}_{-1.5} \pm 8.2^{+7.4}_{-7.4}$	$97.3^{+2.4}_{-2.4} \pm 8.0^{+7.1}_{-7.1}$	
[1, 2]	$255^{+3}_{-3} \pm 21^{+19}_{-19}$	$252^{+1}_{-1} \pm 13^{+15}_{-15}$	$222^{+1}_{-1} \pm 11^{+12}_{-12}$	$184^{+1}_{-1} \pm 10^{+10}_{-10}$	$130.1^{+2.1}_{-2.1} \pm 8.2^{+7.9}_{-7.9}$	
[2, 3]	$147.0^{+1.5}_{-1.5} \pm 9.4^{+9.1}_{-9.1}$	$139.7^{+0.8}_{-0.8} \pm 6.8^{+8.1}_{-8.1}$	$113.7^{+0.7}_{-0.7} \pm 6.1^{+5.9}_{-5.9}$	$92.2^{+0.8}_{-0.8} \pm 5.2^{+5.1}_{-5.1}$	$59.2^{+1.1}_{-1.1} \pm 3.5^{+3.4}_{-3.4}$	
[3, 4]	$66.7^{+0.7}_{-0.7} \pm 3.9^{+3.7}_{-3.7}$	$60.8^{+0.4}_{-0.4} \pm 3.1^{+3.3}_{-3.3}$	$49.0^{+0.4}_{-0.4} \pm 2.6^{+2.5}_{-2.5}$	$37.9^{+0.4}_{-0.4} \pm 2.2^{+2.1}_{-2.1}$	$21.6^{+0.6}_{-0.6} \pm 1.8^{+1.6}_{-1.6}$	
[4, 5]	$30.4^{+0.4}_{-0.4} \pm 1.6^{+1.8}_{-1.8}$	$26.0^{+0.2}_{-0.2} \pm 1.4^{+1.4}_{-1.4}$	$20.5^{+0.2}_{-0.2} \pm 1.2^{+1.0}_{-1.0}$	$14.96^{+0.23}_{-0.23} \pm 0.85^{+0.77}_{-0.77}$	$8.6^{+0.4}_{-0.4} \pm 1.5^{+1.1}_{-1.1}$	
[5, 6]	$13.83^{+0.23}_{-0.23} \pm 0.74^{+0.79}_{-0.79}$	$11.84^{+0.15}_{-0.15} \pm 0.61^{+0.67}_{-0.67}$	$9.34^{+0.14}_{-0.14} \pm 0.58^{+0.47}_{-0.47}$	$6.62^{+0.16}_{-0.16} \pm 0.46^{+0.39}_{-0.39}$	$1.95^{+0.28}_{-0.28} \pm 0.67^{+0.41}_{-0.41}$	
[6, 7]	$7.25^{+0.15}_{-0.15} \pm 0.40^{+0.42}_{-0.42}$	$5.83^{+0.11}_{-0.11} \pm 0.32^{+0.34}_{-0.34}$	$4.41^{+0.09}_{-0.09} \pm 0.27^{+0.22}_{-0.22}$	$2.65^{+0.10}_{-0.10} \pm 0.28^{+0.22}_{-0.22}$		
[7, 8]	$3.80^{+0.10}_{-0.10} \pm 0.22^{+0.23}_{-0.23}$	$3.23^{+0.08}_{-0.08} \pm 0.21^{+0.18}_{-0.18}$	$2.29^{+0.07}_{-0.07} \pm 0.16^{+0.13}_{-0.13}$	$1.26^{+0.09}_{-0.09} \pm 0.25^{+0.18}_{-0.18}$		
[8, 9]	$2.23^{+0.08}_{-0.08} \pm 0.15^{+0.15}_{-0.15}$	$1.71^{+0.06}_{-0.06} \pm 0.12^{+0.11}_{-0.11}$	$1.27^{+0.05}_{-0.05} \pm 0.12^{+0.10}_{-0.10}$	$0.46^{+0.06}_{-0.06} \pm 0.11^{+0.08}_{-0.08}$		
[9, 10]	$1.43^{+0.06}_{-0.06} \pm 0.10^{+0.11}_{-0.11}$	$0.978^{+0.041}_{-0.041} \pm 0.076^{+0.066}_{-0.066}$	$0.556^{+0.035}_{-0.035} \pm 0.077^{+0.060}_{-0.060}$			

**Table 6.** Differential production cross-sections,  $d^2\sigma/(dp_T dy)$ , in  $\mu\text{b}/(\text{GeV}/c)$  for prompt  $D^0 + \bar{D}^0$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

$p_T$ [GeV/c]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[0, 1]		$74 \pm 7 \pm 10$	$58.2 \pm 3.5 \pm 7.0$	$58.6 \pm 4.1 \pm 6.9$		
[1, 2]	$91 \pm 3 \pm 14$	$94.3 \pm 1.0 \pm 7.4$	$89.6 \pm 0.8 \pm 8.0$	$70.1 \pm 0.8 \pm 5.6$	$54.2 \pm 1.3 \pm 4.9$	
[2, 3]	$57.4 \pm 0.8 \pm 6.2$	$55.8 \pm 0.4 \pm 3.7$	$47.7 \pm 0.3 \pm 3.7$	$37.6 \pm 0.3 \pm 2.9$	$25.0 \pm 0.4 \pm 1.9$	
[3, 4]	$28.0 \pm 0.4 \pm 2.4$	$25.6 \pm 0.2 \pm 1.5$	$21.0 \pm 0.1 \pm 1.4$	$16.0 \pm 0.1 \pm 1.1$	$10.26 \pm 0.19 \pm 0.82$	
[4, 5]	$13.7 \pm 0.2 \pm 1.0$	$11.39 \pm 0.10 \pm 0.71$	$9.15 \pm 0.09 \pm 0.62$	$6.52 \pm 0.08 \pm 0.44$	$3.86 \pm 0.11 \pm 0.30$	
[5, 6]	$6.30 \pm 0.11 \pm 0.45$	$5.41 \pm 0.06 \pm 0.34$	$4.13 \pm 0.05 \pm 0.28$	$2.90 \pm 0.05 \pm 0.20$	$1.52 \pm 0.08 \pm 0.15$	
[6, 7]	$3.29 \pm 0.07 \pm 0.23$	$2.64 \pm 0.04 \pm 0.17$	$2.10 \pm 0.04 \pm 0.15$	$1.249 \pm 0.034 \pm 0.095$	$0.709 \pm 0.068 \pm 0.082$	
[7, 8]	$1.83 \pm 0.05 \pm 0.13$	$1.366 \pm 0.028 \pm 0.089$	$1.037 \pm 0.025 \pm 0.073$	$0.693 \pm 0.027 \pm 0.063$		
[8, 9]	$1.025 \pm 0.033 \pm 0.072$	$0.775 \pm 0.021 \pm 0.052$	$0.554 \pm 0.019 \pm 0.044$	$0.393 \pm 0.024 \pm 0.050$		
[9, 10]	$0.555 \pm 0.023 \pm 0.043$	$0.423 \pm 0.015 \pm 0.030$	$0.295 \pm 0.013 \pm 0.029$	$0.162 \pm 0.016 \pm 0.028$		

**Table 7.** Differential production cross-sections,  $d^2\sigma/(dp_T dy)$ , in  $\text{pb}/(\text{GeV}/c)$  for prompt  $D^+$  and  $D^-$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[1, 2]	$29.8^{+4.6}_{-4.6}$	$41.6^{+2.5}_{-2.5}$	$36.0^{+2.3}_{-2.2}$	$25.3^{+2.3}_{-2.3}$	$9.3^{+1.0}_{-1.0}$	$1.5^{+1.5}_{-1.2}$
[2, 3]	$27.3^{+5.1}_{-1.5}$	$27.4^{+0.8}_{-0.8}$	$22.4^{+0.7}_{-0.7}$	$14.6^{+0.6}_{-0.6}$	$9.3^{+1.0}_{-1.0}$	$1.5^{+1.5}_{-1.2}$
[3, 4]	$12.5^{+1.7}_{-0.6}$	$12.4^{+0.4}_{-0.4}$	$9.42^{+0.30}_{-0.30}$	$7.57^{+0.32}_{-0.32}$	$4.49^{+0.42}_{-0.42}$	$0.52^{+0.52}_{-0.42}$
[4, 5]	$5.96^{+0.30}_{-0.30}$	$5.71^{+0.20}_{-0.20}$	$4.52^{+0.18}_{-0.18}$	$2.81^{+0.16}_{-0.16}$	$1.94^{+0.24}_{-0.24}$	$0.25^{+0.25}_{-0.18}$
[5, 6]	$2.73^{+0.18}_{-0.17}$	$2.18^{+0.11}_{-0.11}$	$2.30^{+0.11}_{-0.11}$	$1.36^{+0.10}_{-0.10}$	$0.78^{+0.15}_{-0.15}$	$0.08^{+0.12}_{-0.08}$
[6, 7]	$1.47^{+0.11}_{-0.11}$	$1.31^{+0.08}_{-0.08}$	$0.843^{+0.062}_{-0.062}$	$0.586^{+0.065}_{-0.065}$		
[7, 8]	$0.97^{+0.09}_{-0.09}$	$0.642^{+0.052}_{-0.052}$	$0.461^{+0.044}_{-0.044}$	$0.323^{+0.046}_{-0.046}$		
[8, 9]	$0.379^{+0.052}_{-0.052}$	$0.311^{+0.035}_{-0.035}$	$0.256^{+0.034}_{-0.034}$			
[9, 10]	$0.284^{+0.042}_{-0.042}$	$0.212^{+0.028}_{-0.028}$	$0.147^{+0.025}_{-0.025}$			

**Table 8.** Differential production cross-sections,  $d^2\sigma/(dp_T dy)$ , in  $\mu\text{b}/(\text{GeV}/c)$  for prompt  $D_s^+ + D_s^-$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[1, 2]		$106^{+11}_{-5}$	$88.4^{+2.0}_{-2.0}$	$68.7^{+1.9}_{-1.9}$	$45.0^{+2.7}_{-2.7}$	$3.9^{+3.9}_{-4.4}$
[2, 3]	$68.8^{+6.8}_{-6.8}$	$63.0^{+1.5}_{-1.5}$	$50.0^{+0.8}_{-0.8}$	$36.1^{+0.8}_{-0.8}$	$24.8^{+1.2}_{-1.2}$	$2.9^{+2.9}_{-2.7}$
[3, 4]	$34.9^{+1.7}_{-1.7}$	$28.6^{+0.6}_{-0.6}$	$23.4^{+0.4}_{-0.4}$	$15.8^{+0.4}_{-0.4}$	$9.46^{+0.59}_{-0.59}$	$0.72^{+0.72}_{-0.79}$
[4, 5]	$15.5^{+0.7}_{-0.7}$	$12.76^{+0.29}_{-0.29}$	$10.17^{+0.23}_{-0.23}$	$7.53^{+0.24}_{-0.24}$	$3.61^{+0.40}_{-0.40}$	$0.82^{+0.82}_{-0.55}$
[5, 6]	$7.30^{+0.35}_{-0.35}$	$5.63^{+0.16}_{-0.16}$	$4.40^{+0.14}_{-0.14}$	$3.07^{+0.15}_{-0.15}$	$1.93^{+0.06}_{-0.06}$	$0.31^{+0.31}_{-0.25}$
[6, 7]	$4.09^{+0.22}_{-0.22}$	$2.87^{+0.11}_{-0.11}$	$2.14^{+0.09}_{-0.09}$	$1.43^{+0.10}_{-0.10}$		
[7, 8]	$1.86^{+0.13}_{-0.13}$	$1.57^{+0.08}_{-0.08}$	$1.15^{+0.06}_{-0.06}$	$0.690^{+0.081}_{-0.081}$		
[8, 9]	$0.984^{+0.085}_{-0.085}$	$0.866^{+0.054}_{-0.054}$	$0.622^{+0.047}_{-0.047}$	$0.40^{+0.07}_{-0.07}$		
[9, 10]	$0.758^{+0.073}_{-0.073}$	$0.488^{+0.040}_{-0.040}$	$0.470^{+0.044}_{-0.044}$			

**Table 9.** Differential production cross-sections,  $d^2\sigma/(dp_T dy)$ , in  $\mu\text{b}/(\text{GeV}/c)$  for prompt  $D^{*+} + D^{*-}$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.



## B Cross-section ratios at different energies

Tables 10–13 give the numerical results of the cross-section ratios between  $\sqrt{s} = 13$  and 5 TeV.

$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[0, 1]	$1.49^{+0.03+0.23}_{-0.03-0.20}$	$1.61^{+0.01+0.13}_{-0.01-0.15}$	$1.72^{+0.02+0.13}_{-0.02-0.10}$	$1.88^{+0.02+0.12}_{-0.02-0.11}$	$2.12^{+0.06+0.20}_{-0.05-0.19}$	
[1, 2]	$1.61^{+0.02+0.20}_{-0.02-0.18}$	$1.72^{+0.01+0.13}_{-0.01-0.12}$	$1.88^{+0.01+0.12}_{-0.01-0.10}$	$2.04^{+0.02+0.12}_{-0.02-0.11}$	$2.31^{+0.04+0.17}_{-0.04-0.14}$	
[2, 3]	$1.78^{+0.02+0.15}_{-0.02-0.17}$	$1.94^{+0.01+0.14}_{-0.01-0.10}$	$2.20^{+0.02+0.13}_{-0.02-0.11}$	$2.35^{+0.02+0.15}_{-0.02-0.12}$	$2.70^{+0.05+0.17}_{-0.05-0.17}$	
[3, 4]	$2.03^{+0.02+0.14}_{-0.02-0.16}$	$2.20^{+0.02+0.14}_{-0.02-0.11}$	$2.35^{+0.02+0.14}_{-0.02-0.12}$	$2.69^{+0.03+0.19}_{-0.03-0.16}$	$3.33^{+0.09+0.32}_{-0.09-0.31}$	
[4, 5]	$2.19^{+0.03+0.17}_{-0.03-0.13}$	$2.48^{+0.03+0.16}_{-0.02-0.12}$	$2.65^{+0.03+0.16}_{-0.03-0.14}$	$3.07^{+0.05+0.17}_{-0.05-0.19}$	$3.04^{+0.16+0.63}_{-0.15-0.55}$	
[5, 6]	$2.57^{+0.05+0.21}_{-0.04-0.15}$	$2.66^{+0.04+0.17}_{-0.04-0.13}$	$2.90^{+0.05+0.16}_{-0.04-0.18}$	$3.15^{+0.08+0.22}_{-0.08-0.21}$	$5.6^{+1.0+2.2}_{-0.7-1.6}$	
[6, 7]	$2.55^{+0.06+0.19}_{-0.05-0.16}$	$2.95^{+0.06+0.19}_{-0.06-0.16}$	$3.27^{+0.07+0.18}_{-0.07-0.21}$	$3.85^{+0.16+0.44}_{-0.15-0.44}$		
[7, 8]	$2.67^{+0.08+0.22}_{-0.08-0.17}$	$3.00^{+0.08+0.20}_{-0.07-0.18}$	$3.44^{+0.11+0.21}_{-0.10-0.26}$	$3.93^{+0.32+0.91}_{-0.28-0.73}$		

**Table 10.** The ratios of differential production cross-sections,  $R_{13/5}$ , for prompt  $D^0 + \bar{D}^0$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[0, 1]		$2.10^{+0.23+0.69}_{-0.19-0.44}$	$1.83^{+0.12+0.32}_{-0.11-0.28}$	$1.66^{+0.13+0.28}_{-0.12-0.25}$		
[1, 2]	$1.80^{+0.07+0.44}_{-0.07-0.38}$	$1.69^{+0.02+0.31}_{-0.02-0.20}$	$1.88^{+0.02+0.18}_{-0.02-0.19}$	$2.08^{+0.03+0.17}_{-0.03-0.17}$	$2.25^{+0.06+0.24}_{-0.06-0.22}$	
[2, 3]	$1.72^{+0.03+0.30}_{-0.03-0.27}$	$1.97^{+0.01+0.25}_{-0.01-0.18}$	$2.09^{+0.01+0.15}_{-0.01-0.17}$	$2.25^{+0.02+0.15}_{-0.02-0.16}$	$2.64^{+0.05+0.22}_{-0.04-0.19}$	
[3, 4]	$1.87^{+0.03+0.28}_{-0.03-0.26}$	$2.21^{+0.02+0.22}_{-0.02-0.17}$	$2.41^{+0.02+0.18}_{-0.02-0.15}$	$2.60^{+0.03+0.18}_{-0.03-0.15}$	$2.81^{+0.06+0.21}_{-0.05-0.21}$	
[4, 5]	$2.12^{+0.03+0.27}_{-0.03-0.26}$	$2.48^{+0.02+0.22}_{-0.02-0.17}$	$2.55^{+0.03+0.19}_{-0.03-0.14}$	$2.96^{+0.04+0.21}_{-0.04-0.17}$	$3.59^{+0.11+0.23}_{-0.10-0.29}$	
[5, 6]	$2.40^{+0.04+0.25}_{-0.04-0.27}$	$2.68^{+0.03+0.22}_{-0.03-0.17}$	$2.95^{+0.04+0.21}_{-0.04-0.16}$	$3.25^{+0.06+0.24}_{-0.06-0.20}$	$4.51^{+0.24+0.47}_{-0.22-0.48}$	
[6, 7]	$2.54^{+0.06+0.25}_{-0.06-0.25}$	$2.80^{+0.05+0.22}_{-0.05-0.17}$	$3.01^{+0.06+0.22}_{-0.06-0.17}$	$3.92^{+0.11+0.25}_{-0.11-0.29}$	$4.27^{+0.48+0.61}_{-0.39-0.50}$	
[7, 8]	$2.72^{+0.08+0.28}_{-0.07-0.24}$	$3.10^{+0.07+0.25}_{-0.07-0.19}$	$3.39^{+0.09+0.27}_{-0.08-0.20}$	$3.70^{+0.16+0.29}_{-0.14-0.34}$		

**Table 11.** The ratios of differential production cross-sections,  $R_{13/5}$ , for prompt  $D^+ + D^-$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

$p_T$ [GeV/ $c$ ]	$y$				
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]
[1, 2]	$1.30^{+0.28+0.54}_{-0.21-0.37}$	$1.48^{+0.12+0.42}_{-0.10-0.24}$	$1.83^{+0.14+0.26}_{-0.12-0.24}$	$2.30^{+0.26+0.41}_{-0.22-0.31}$	
[2, 3]	$1.58^{+0.10+0.41}_{-0.09-0.32}$	$1.76^{+0.05+0.24}_{-0.05-0.17}$	$2.10^{+0.07+0.19}_{-0.06-0.17}$	$2.77^{+0.13+0.22}_{-0.13-0.22}$	$2.71^{+0.36+0.45}_{-0.28-0.38}$
[3, 4]	$1.94^{+0.10+0.35}_{-0.09-0.30}$	$2.06^{+0.06+0.21}_{-0.06-0.19}$	$2.44^{+0.08+0.20}_{-0.08-0.16}$	$2.58^{+0.12+0.20}_{-0.11-0.18}$	$2.75^{+0.30+0.32}_{-0.25-0.27}$
[4, 5]	$2.09^{+0.12+0.33}_{-0.11-0.26}$	$2.35^{+0.09+0.23}_{-0.08-0.17}$	$2.38^{+0.10+0.18}_{-0.09-0.15}$	$3.42^{+0.21+0.25}_{-0.19-0.26}$	$3.28^{+0.48+0.41}_{-0.38-0.33}$
[5, 6]	$2.82^{+0.20+0.35}_{-0.18-0.33}$	$3.26^{+0.18+0.33}_{-0.16-0.20}$	$2.56^{+0.14+0.20}_{-0.13-0.18}$	$3.39^{+0.29+0.38}_{-0.25-0.26}$	$4.0^{+1.0+0.7}_{-0.7-0.6}$
[6, 7]	$2.60^{+0.23+0.32}_{-0.19-0.28}$	$2.94^{+0.20+0.28}_{-0.18-0.22}$	$3.59^{+0.30+0.29}_{-0.26-0.28}$	$3.58^{+0.47+0.49}_{-0.37-0.34}$	
[7, 8]	$2.50^{+0.27+0.37}_{-0.22-0.22}$	$2.79^{+0.26+0.24}_{-0.22-0.25}$	$3.47^{+0.38+0.37}_{-0.32-0.29}$	$4.12^{+0.72+0.76}_{-0.55-0.56}$	

**Table 12.** The ratios of differential production cross-sections,  $R_{13/5}$ , for prompt  $D_s^+ + D_s^-$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[1, 2]		$1.33^{+0.07+0.15}_{-0.06-0.15}$	$1.70^{+0.04+0.19}_{-0.04-0.17}$	$1.81^{+0.06+0.21}_{-0.05-0.17}$	$2.52^{+0.17+0.40}_{-0.15-0.25}$	
[2, 3]	$1.51^{+0.18+0.32}_{-0.16-0.30}$	$1.70^{+0.04+0.20}_{-0.04-0.14}$	$2.01^{+0.04+0.21}_{-0.03-0.18}$	$2.29^{+0.06+0.27}_{-0.05-0.19}$	$2.47^{+0.13+0.33}_{-0.12-0.29}$	
[3, 4]	$1.60^{+0.09+0.20}_{-0.08-0.21}$	$1.99^{+0.04+0.18}_{-0.04-0.19}$	$2.08^{+0.04+0.21}_{-0.04-0.17}$	$2.49^{+0.07+0.28}_{-0.07-0.21}$	$3.00^{+0.20+0.35}_{-0.18-0.26}$	
[4, 5]	$1.82^{+0.09+0.21}_{-0.08-0.21}$	$2.18^{+0.05+0.20}_{-0.05-0.20}$	$2.25^{+0.05+0.20}_{-0.05-0.18}$	$2.54^{+0.09+0.30}_{-0.08-0.24}$	$3.24^{+0.42+0.77}_{-0.33-0.62}$	
[5, 6]	$1.96^{+0.10+0.21}_{-0.09-0.22}$	$2.43^{+0.08+0.22}_{-0.07-0.22}$	$2.72^{+0.09+0.25}_{-0.09-0.22}$	$3.22^{+0.17+0.33}_{-0.15-0.25}$	$2.61^{+0.16+0.65}_{-0.16-0.50}$	
[6, 7]	$2.07^{+0.13+0.22}_{-0.11-0.23}$	$2.72^{+0.11+0.25}_{-0.10-0.24}$	$2.95^{+0.13+0.26}_{-0.12-0.25}$	$3.10^{+0.25+0.32}_{-0.22-0.26}$		
[7, 8]	$2.67^{+0.20+0.30}_{-0.18-0.29}$	$2.71^{+0.14+0.27}_{-0.13-0.24}$	$3.23^{+0.20+0.31}_{-0.18-0.27}$	$3.89^{+0.53+0.61}_{-0.42-0.47}$		

**Table 13.** The ratios of differential production cross-sections,  $R_{13/5}$ , for prompt  $D^{*+} + D^{*-}$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic.

## C Cross-section ratios for different mesons

The numerical values of the cross-section ratios between mesons, described in section 5, are given in  $(p_T, y)$  bins in tables 14–19.

$p_T$ [GeV/ $c$ ]	$y$				
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]
[0, 1]		$101 \pm 9 \pm 12$	$83.9 \pm 5.0 \pm 8.4$	$101.0 \pm 7.2 \pm 9.9$	
[1, 2]	$84 \pm 3 \pm 11$	$88.2 \pm 1.1 \pm 3.6$	$94.9 \pm 1.0 \pm 5.4$	$89.4 \pm 1.2 \pm 4.2$	$98.1 \pm 2.9 \pm 7.2$
[2, 3]	$91.9 \pm 1.7 \pm 7.3$	$94.0 \pm 0.8 \pm 2.8$	$98.7 \pm 0.9 \pm 3.9$	$95.9 \pm 1.1 \pm 4.0$	$99.4 \pm 2.4 \pm 5.2$
[3, 4]	$98.8 \pm 1.7 \pm 4.8$	$99.0 \pm 1.0 \pm 2.0$	$101.0 \pm 1.1 \pm 2.9$	$99.0 \pm 1.4 \pm 3.4$	$111.8 \pm 3.6 \pm 8.1$
[4, 5]	$106.2 \pm 2.0 \pm 4.4$	$103.1 \pm 1.4 \pm 2.5$	$104.9 \pm 1.5 \pm 3.3$	$102.6 \pm 2.1 \pm 3.4$	$106 \pm 6 \pm 16$
[5, 6]	$107.2 \pm 2.6 \pm 4.4$	$107.5 \pm 1.9 \pm 3.5$	$104.1 \pm 2.1 \pm 3.3$	$103.2 \pm 3.1 \pm 5.1$	$184 \pm 32 \pm 58$
[6, 7]	$106.6 \pm 3.2 \pm 4.5$	$106.7 \pm 2.6 \pm 3.8$	$111.8 \pm 3.1 \pm 4.3$	$110.7 \pm 5.4 \pm 9.7$	
[7, 8]	$113.6 \pm 4.4 \pm 5.5$	$99.4 \pm 3.3 \pm 3.4$	$106.4 \pm 4.1 \pm 5.2$	$130 \pm 11 \pm 24$	
[8, 9]	$108.4 \pm 5.4 \pm 6.4$	$106.4 \pm 4.7 \pm 4.9$	$102.7 \pm 5.7 \pm 7.2$	$202 \pm 35 \pm 53$	
[9, 10]	$91.3 \pm 5.6 \pm 7.0$	$101.9 \pm 5.8 \pm 6.3$	$125 \pm 10 \pm 17$		

**Table 14.** The ratios of the measurements of cross-section times branching fraction for prompt  $D^+$  and  $D^0$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic. All values are given in percent.

$p_T$ [GeV/ $c$ ]	$y$				
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]
[1, 2]	$6.8^{+1.0}_{-1.0} +^{1.5}_{-1.1}$	$9.56^{+0.57}_{-0.58} +^{0.54}_{-0.60}$	$9.37^{+0.58}_{-0.59} +^{0.72}_{-0.52}$	$7.91^{+0.72}_{-0.73} +^{0.66}_{-0.49}$	
[2, 3]	$10.7^{+0.6}_{-0.6} +^{1.7}_{-1.3}$	$11.31^{+0.32}_{-0.32} +^{0.38}_{-0.47}$	$11.39^{+0.34}_{-0.35} +^{0.52}_{-0.40}$	$9.17^{+0.41}_{-0.41} +^{0.48}_{-0.35}$	$9.1^{+1.0}_{-1.0} +^{1.2}_{-0.9}$
[3, 4]	$10.80^{+0.52}_{-0.53} +^{0.98}_{-0.79}$	$11.76^{+0.35}_{-0.34} +^{0.30}_{-0.45}$	$11.10^{+0.36}_{-0.36} +^{0.43}_{-0.33}$	$11.53^{+0.50}_{-0.52} +^{0.52}_{-0.45}$	$12.0^{+1.2}_{-1.2} +^{1.0}_{-1.0}$
[4, 5]	$11.30^{+0.59}_{-0.58} +^{0.67}_{-0.77}$	$12.67^{+0.45}_{-0.46} +^{0.32}_{-0.51}$	$12.70^{+0.52}_{-0.52} +^{0.49}_{-0.45}$	$10.84^{+0.62}_{-0.62} +^{0.51}_{-0.40}$	$13.0^{+1.7}_{-1.7} +^{2.3}_{-2.0}$
[5, 6]	$11.41^{+0.75}_{-0.75} +^{0.63}_{-0.65}$	$10.62^{+0.55}_{-0.53} +^{0.39}_{-0.41}$	$14.23^{+0.75}_{-0.72} +^{0.61}_{-0.62}$	$11.88^{+0.96}_{-0.94} +^{0.72}_{-0.76}$	$23.1^{+6.3}_{-5.2} +^{7.6}_{-5.7}$
[6, 7]	$11.75^{+0.92}_{-0.94} +^{0.70}_{-0.75}$	$12.98^{+0.86}_{-0.82} +^{0.71}_{-0.54}$	$11.05^{+0.85}_{-0.85} +^{0.59}_{-0.52}$	$12.8^{+1.5}_{-1.5} +^{1.5}_{-1.3}$	
[7, 8]	$14.7^{+1.4}_{-1.4} +^{0.9}_{-1.2}$	$11.47^{+0.97}_{-0.97} +^{0.78}_{-0.56}$	$11.6^{+1.2}_{-1.2} +^{0.8}_{-0.8}$	$14.8^{+2.5}_{-2.3} +^{3.5}_{-2.6}$	
[8, 9]	$9.8^{+1.4}_{-1.4} +^{0.8}_{-0.7}$	$10.5^{+1.2}_{-1.2} +^{0.8}_{-0.7}$	$11.6^{+1.6}_{-1.5} +^{1.3}_{-1.1}$		
[9, 10]	$11.4^{+1.8}_{-1.8} +^{1.3}_{-1.2}$	$12.5^{+1.8}_{-1.7} +^{1.3}_{-1.0}$	$15.2^{+2.9}_{-2.7} +^{2.7}_{-2.1}$		

**Table 15.** The ratios of the measurements of cross-section times branching fraction for prompt  $D_s^+$  and  $D^0$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic. All values are given in percent.

$p_T$ [GeV/ $c$ ]	$y$				
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]
[1, 2]		$28.6^{+1.3+2.1}_{-1.3-1.2}$	$26.9^{+0.6+1.5}_{-0.6-1.7}$	$25.2^{+0.7+1.5}_{-0.7-1.7}$	$23.4^{+1.4+1.6}_{-1.4-1.9}$
[2, 3]	$31.7^{+3.2+3.0}_{-3.1-3.2}$	$30.5^{+0.7+1.1}_{-0.7-1.2}$	$29.8^{+0.5+1.5}_{-0.5-1.9}$	$26.5^{+0.7+1.5}_{-0.7-1.8}$	$28.3^{+1.5+2.9}_{-1.4-2.7}$
[3, 4]	$35.4^{+1.8+1.5}_{-1.8-2.1}$	$31.9^{+0.7+1.3}_{-0.7-1.1}$	$32.4^{+0.7+1.9}_{-0.6-1.7}$	$28.2^{+0.8+1.6}_{-0.8-1.9}$	$29.7^{+2.0+2.1}_{-2.0-2.5}$
[4, 5]	$34.5^{+1.6+1.6}_{-1.6-1.7}$	$33.2^{+0.8+1.2}_{-0.8-1.4}$	$33.6^{+0.9+2.0}_{-0.8-1.6}$	$34.1^{+1.2+2.4}_{-1.2-2.6}$	$28.4^{+3.5+7.5}_{-3.4-5.5}$
[5, 6]	$35.8^{+1.8+1.8}_{-1.8-1.9}$	$32.2^{+1.0+1.4}_{-1.0-1.4}$	$31.9^{+1.1+1.8}_{-1.1-1.7}$	$31.4^{+1.7+2.3}_{-1.6-2.0}$	$67^{+11+23}_{-9-17}$
[6, 7]	$38.1^{+2.2+2.0}_{-2.2-2.2}$	$33.4^{+1.4+1.5}_{-1.4-1.6}$	$32.9^{+1.6+1.8}_{-1.6-1.8}$	$36.6^{+3.0+3.5}_{-3.0-3.7}$	
[7, 8]	$33.2^{+2.4+2.0}_{-2.4-2.2}$	$32.9^{+1.8+1.5}_{-1.8-2.0}$	$33.9^{+2.2+2.3}_{-2.1-2.2}$	$37.2^{+5.2+7.1}_{-5.0-6.3}$	
[8, 9]	$29.9^{+2.8+2.2}_{-2.8-2.4}$	$34.2^{+2.5+1.9}_{-2.3-2.4}$	$33.2^{+3.0+3.2}_{-2.8-2.8}$	$59^{+14+24}_{-12-13}$	
[9, 10]	$35.8^{+3.9+3.1}_{-3.8-3.0}$	$33.8^{+3.1+2.3}_{-3.0-2.9}$	$57.2^{+6.5+9.6}_{-6.3-8.1}$		

**Table 16.** The ratios of the measurements of cross-section times branching fraction for prompt  $D^{*+}$  and  $D^0$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic. All values are given in percent.

$p_T$ [GeV/ $c$ ]	$y$				
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]
[1, 2]	$8.0 \pm 1.3 \pm 2.1$ $1.2 - 1.5$	$10.84 \pm 0.67 \pm 0.55$ $0.66 - 0.54$	$9.87 \pm 0.62 \pm 0.47$ $0.63 - 0.55$	$8.84 \pm 0.82 \pm 0.60$ $0.82 - 0.58$	
[2, 3]	$11.7 \pm 0.7 \pm 1.9$ $0.6 - 1.5$	$12.03 \pm 0.33 \pm 0.34$ $0.34 - 0.28$	$11.53 \pm 0.35 \pm 0.33$ $0.34 - 0.35$	$9.56 \pm 0.42 \pm 0.38$ $0.42 - 0.38$	$9.2 \pm 1.0 \pm 1.3$ $1.0 - 0.9$
[3, 4]	$10.9 \pm 0.5 \pm 1.1$ $0.5 - 0.8$	$11.87 \pm 0.35 \pm 0.36$ $0.34 - 0.17$	$10.99 \pm 0.36 \pm 0.40$ $0.36 - 0.21$	$11.63 \pm 0.51 \pm 0.54$ $0.51 - 0.33$	$10.7 \pm 1.0 \pm 0.9$ $1.0 - 0.8$
[4, 5]	$10.64 \pm 0.56 \pm 0.68$ $0.56 - 0.64$	$12.29 \pm 0.45 \pm 0.34$ $0.44 - 0.33$	$12.11 \pm 0.49 \pm 0.47$ $0.50 - 0.35$	$10.57 \pm 0.61 \pm 0.52$ $0.60 - 0.36$	$12.3 \pm 1.6 \pm 1.1$ $1.6 - 0.9$
[5, 6]	$10.64 \pm 0.72 \pm 0.54$ $0.71 - 0.53$	$9.88 \pm 0.51 \pm 0.38$ $0.50 - 0.28$	$13.68 \pm 0.70 \pm 0.61$ $0.69 - 0.45$	$11.52 \pm 0.91 \pm 0.71$ $0.90 - 0.56$	$12.6 \pm 2.6 \pm 1.7$ $2.6 - 1.3$
[6, 7]	$11.01 \pm 0.89 \pm 0.64$ $0.87 - 0.57$	$12.17 \pm 0.79 \pm 0.64$ $0.77 - 0.37$	$9.87 \pm 0.75 \pm 0.63$ $0.74 - 0.40$	$11.5 \pm 1.3 \pm 1.1$ $1.3 - 0.8$	
[7, 8]	$13.0 \pm 1.2 \pm 0.9$ $1.2 - 0.9$	$11.53 \pm 0.97 \pm 0.88$ $0.97 - 0.39$	$10.9 \pm 1.1 \pm 0.8$ $1.1 - 0.5$	$11.4 \pm 1.7 \pm 1.8$ $1.7 - 1.3$	
[8, 9]	$9.1 \pm 1.3 \pm 0.8$ $1.3 - 0.6$	$9.9 \pm 1.2 \pm 0.9$ $1.1 - 0.4$	$11.4 \pm 1.5 \pm 1.1$ $1.5 - 0.9$		
[9, 10]	$12.5 \pm 1.9 \pm 1.4$ $1.9 - 1.1$	$12.3 \pm 1.7 \pm 1.4$ $1.7 - 0.7$	$12.2 \pm 2.2 \pm 1.5$ $2.1 - 1.3$		

**Table 17.** The ratios of the measurements of cross-section times branching fraction for prompt  $D_s^+$  and  $D^+$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic. All values are given in percent.



$p_T$ [GeV/ $c$ ]	$y$					
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]	
[1, 2]		$32.5^{+1.5+2.2}_{-1.5-0.8}$	$28.4^{+0.7+0.5}_{-0.7-1.6}$	$28.2^{+0.9+0.9}_{-0.9-1.6}$	$23.9^{+1.6+1.6}_{-1.5-2.0}$	
[2, 3]	$34.5^{+3.4+3.8}_{-3.5-3.9}$	$32.4^{+0.8+1.1}_{-0.8-0.9}$	$30.2^{+0.5+0.8}_{-0.5-1.5}$	$27.6^{+0.7+0.9}_{-0.7-1.5}$	$28.5^{+1.5+2.8}_{-1.4-2.5}$	
[3, 4]	$35.8^{+1.8+2.2}_{-1.8-2.2}$	$32.2^{+0.7+1.4}_{-0.7-0.4}$	$32.1^{+0.6+1.6}_{-0.6-1.2}$	$28.5^{+0.8+1.4}_{-0.8-1.5}$	$26.5^{+1.7+1.4}_{-1.7-1.7}$	
[4, 5]	$32.5^{+1.5+1.7}_{-1.5-1.4}$	$32.2^{+0.8+1.1}_{-0.8-0.9}$	$32.0^{+0.8+1.7}_{-0.8-1.1}$	$33.2^{+1.1+2.2}_{-1.1-2.2}$	$26.9^{+3.1+5.8}_{-3.1-4.0}$	
[5, 6]	$33.4^{+1.7+1.5}_{-1.7-1.5}$	$29.9^{+1.0+1.1}_{-0.9-1.0}$	$30.6^{+1.1+1.6}_{-1.1-1.2}$	$30.5^{+1.6+1.9}_{-1.6-1.3}$	$36.6^{+2.2+5.8}_{-2.0-4.7}$	
[6, 7]	$35.8^{+2.1+1.8}_{-2.1-1.7}$	$31.3^{+1.3+1.2}_{-1.2-1.2}$	$29.4^{+1.4+1.6}_{-1.4-1.3}$	$33.1^{+2.6+2.1}_{-2.5-2.1}$		
[7, 8]	$29.2^{+2.1+1.8}_{-2.1-1.6}$	$33.1^{+1.7+1.6}_{-1.7-1.4}$	$31.8^{+2.0+2.0}_{-1.9-1.5}$	$28.6^{+3.6+3.1}_{-3.5-3.0}$		
[8, 9]	$27.6^{+2.5+1.9}_{-2.5-1.8}$	$32.2^{+2.2+1.9}_{-2.2-1.6}$	$32.3^{+2.7+2.5}_{-2.6-2.1}$	$29.0^{+5.4+8.8}_{-5.3-5.6}$		
[9, 10]	$39.3^{+4.2+3.2}_{-4.1-2.9}$	$33.2^{+3.0+2.4}_{-2.9-2.2}$	$45.8^{+4.8+5.8}_{-4.6-5.1}$			

**Table 18.** The ratios of the measurements of cross-section times branching fraction for prompt  $D^{*+}$  and  $D^+$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic. All values are given in percent.

$p_T$ [GeV/ $c$ ]	$y$				
	[2.0, 2.5]	[2.5, 3.0]	[3.0, 3.5]	[3.5, 4.0]	[4.0, 4.5]
[1, 2]		$33.4^{+2.6+1.3}_{-2.4-2.6}$	$34.8^{+2.3+2.7}_{-2.3-1.2}$	$31.4^{+3.0+3.3}_{-3.0-1.9}$	
[2, 3]	$33.8^{+4.2+7.2}_{-3.5-4.6}$	$37.0^{+1.4+1.3}_{-1.3-1.3}$	$38.2^{+1.3+2.3}_{-1.3-1.0}$	$34.6^{+1.7+2.7}_{-1.7-1.6}$	$32.1^{+3.9+5.5}_{-3.8-4.0}$
[3, 4]	$30.5^{+2.2+3.3}_{-2.1-2.1}$	$36.9^{+1.3+0.8}_{-1.3-1.4}$	$34.3^{+1.3+1.7}_{-1.2-1.6}$	$40.8^{+2.1+3.2}_{-2.0-2.1}$	$40.4^{+4.6+4.2}_{-4.5-2.6}$
[4, 5]	$32.8^{+2.3+2.1}_{-2.1-2.1}$	$38.2^{+1.6+1.3}_{-1.6-1.4}$	$37.9^{+1.7+1.8}_{-1.7-2.2}$	$31.9^{+2.0+2.9}_{-2.0-2.1}$	$45.7^{+8.3+9.5}_{-7.1-7.7}$
[5, 6]	$31.9^{+2.7+1.9}_{-2.5-1.7}$	$33.0^{+1.9+1.4}_{-1.8-1.2}$	$44.6^{+2.7+2.6}_{-2.5-2.4}$	$37.8^{+3.5+2.6}_{-3.3-2.7}$	$34.3^{+6.9+6.3}_{-6.8-4.9}$
[6, 7]	$30.8^{+3.0+2.0}_{-2.8-1.8}$	$38.9^{+2.8+2.5}_{-2.8-1.5}$	$33.6^{+2.9+2.4}_{-2.8-1.9}$	$34.8^{+4.8+3.9}_{-4.4-2.6}$	
[7, 8]	$44.5^{+5.2+3.5}_{-5.0-3.0}$	$34.9^{+3.3+3.0}_{-3.3-1.4}$	$34.3^{+4.0+2.9}_{-3.7-2.3}$	$40.0^{+8.1+7.6}_{-7.1-4.8}$	
[8, 9]	$32.9^{+5.5+3.3}_{-5.2-2.7}$	$30.6^{+4.1+3.1}_{-3.9-1.5}$	$35.1^{+5.4+3.8}_{-5.2-3.0}$		
[9, 10]	$31.9^{+6.0+4.3}_{-5.4-3.3}$	$37.0^{+6.0+4.8}_{-5.5-2.6}$	$26.6^{+5.5+4.3}_{-4.9-3.2}$		

**Table 19.** The ratios of the measurements of cross-section times branching fraction for prompt  $D_s^+$  and  $D^{*+}$  mesons in bins of  $(p_T, y)$ . The first uncertainty is statistical, and the second is the total systematic. All values are given in percent.

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## The LHCb collaboration

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